Physiopucks: Increasing User Motivation by Combining Tangible and Implicit Physiological Interaction

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In this article, we evaluate *b-Reactable*, a digital music instrument that combines implicit physiology-based interaction through EEG and ECG, and explicit gestural interaction for sound generation and control. This multimodality is embodied in tangible objects named *physiopucks*, which are driven by biosignals. We hypothesize that multimodality increases users' motivation in a musical task, compared to the use of a gesture-only tabletop system (the *Reactable*). We compared motivational aspects in dyads collaborating in three experimental groups ($N = 56$): the Physio group (one physiology- and one gesture-based user), the Sham group (one prerecorded physiology- and one gesture-based user), and the Control group (two gesture users). Between-group comparisons showed that motivation dimensions of Confidence and Satisfaction were higher in *b-Reactable* than in the gesture-only tangible interface, and that fake physiology-based feedback significantly reduced these effects. Our study also shows the potential of combined implicit and explicit interaction modes in multiuser HCI scenarios.

Categories and Subject Descriptors: H.5.2 [Information Interfaces and Presentation]: User Interfaces—Input devices and strategies; H.5.2 [Information Interfaces and Presentation]: User Interfaces—Evaluation/methodology; K.4.3 [Computers and Society]: Organizational Impacts—Computer-supported collaborative work; H.5.5 [Information Interfaces and Presentation]: Sound and Music Computing—Signal analysis, synthesis, and processing

Q1 General Terms:

Additional Key Words and Phrases: Brain computer interfaces, Brain tangible user interface, computer-supported collaborative work, implicit interaction, human-computer interaction, multimodal interfaces, musical collaboration, physiological computing, physiopucks, tabletops

ACM Reference Format:

S. Mealla Cincuegrani, S. Jordà, and A. Väljamäe. 2015. Physiopucks: Increasing user motivation by combining tangible and implicit physiological interaction. *ACM Trans. Comput.-Hum. Interact.* 23, 1, Article 4 (December 2015), 22 pages.
 DOI: <http://dx.doi.org/10.1145/2838732>

1. INTRODUCTION

Every year, physiological interfaces are becoming more and more pervasive due to the emergence of mobile and wearable devices incorporating biosignal sensing. Consider,

The results leading to this publication have been partially funded by the European Union's Horizon 2020 research and innovation programme through the RAPID-MIX Project (nr 644862) and by TEC2010-11599-E. A. Väljamäe received funding from Marie Curie Actions of the European Union's Seventh Framework Programme (FP7/2007-2013) under REA GA-303172.

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DOI: <http://dx.doi.org/10.1145/2838732>

for example, smart watches with heart rate monitoring, controllers based on electromyography (EMG), and off-the-shelf wireless electroencephalography (EEG) headsets. These new applications have drawn the attention of the human-computer interaction (HCI) community, aiming to design physiological interfaces that can provide meaningful interactions in relevant domains [Fairclough 2011].

Interface design based on physiological computing (PC) normally targets explicit, conscious interface control [Zander 2010] as, for example, in the case of brain computer interfaces (BCIs) [Wolpaw et al. 2002] or muscle-based control [Caramiaux et al. 2015]. However, PC can also be used to achieve implicit and indirect interaction by continuously monitoring the user's physiological activity. In this manner, users' cognitive, perceptual, and emotional states can be classified and subsequently embedded into interactive processes without the user's explicit intention [Bermúdez i Badia et al. 2009; Zander and Jatzev 2009].

Implicit interaction has been explored by different disciplines such as cognitive psychology [Hudlicka 2003], affective computing [Allanson and Fairclough 2004], and enactive media [Tikka et al. 2012]. However, implicit interaction interfaces are still emerging [Zander and Kothe 2011], as most of the current noninvasive PC applications for healthy users are restricted to activity tracking, informing users about their performance in a given physical task such as running or cycling. In this context, we are still in the need of PC systems designed for meaningful HCI scenarios that are thoroughly evaluated and compared to existing interaction paradigms [Fairclough 2011] in order to determine to what extent they might enhance human control bandwidth, especially when combined with traditional user interfaces, and assists human-human communication in multiuser scenarios.

This article explores the possibilities of implicit PC for enriching HCI channels by combining explicit conscious control (i.e., tangible input) and implicit interaction. This approach is applied to an expressive HCI domain: musical performance and sonic interaction design. To perform empirical evaluation, we created a digital musical instrument (DMI) named *b-Reactable*, based on *Reactable*, a renowned musical tabletop system [Jordà 2003]. This DMI can be operated through tangible objects (pucks), but it also incorporates implicit interaction by measuring the participant's brain activity (EEG) and (ECG). Through these measures, we are able to estimate low-level physiological features in real time: user frontal EEG activity and heart rate. These estimations are used for sound synthesis (audification) and for controlling the tempo of the DMI (beats per minute, BPM). These physiological controllers are embodied in two physical objects, named *physiopucks*, allowing users to combine EEG and ECG features with other *Reactable* pucks, such as filters and controllers.

This article significantly extends our previous pilot study with *b-Reactable*, which showed significant differences in motivation levels between participants who were collaborating only via gestures and those who were using *physiopucks* [Mealla et al. 2011]. However, our previous study did not have a balanced number of participants in the two experimental groups and did not have the control group. Therefore, for this article, we extended the study the *b-Reactable*, testing three balanced experimental groups: the Physio group, where the multimodal system was fully functional; the Sham group, where *physiopucks* were driven by prerecorded physiological signals; and the Control group, where no *physiopucks* were present. Thus, participants were using a conventional tabletop system. Importantly, introducing the Control group allowed us to compare the *b-Reactable* user experience to another DMI based on tangible interaction (*Reactable*).

To compare experimental groups, we use a computer-supported cooperative learning approach, which operationalizes user experience in multiple dimensions of motivation [Jones and Issroff 2005]. The main goal of this study is to determine whether the

Fig. 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).

use of multimodal control through gestures and implicit interaction (physiopucks) can influence user motivation in a musical task, compared to the use of a gesture-only tabletop system, Reactable. To this end, we have the following hypotheses:

Hypothesis 1. Motivation of participants working with b-Reactable will be higher than for participants working with the standard Reactable when performing the same musical task. Specifically, participants working with PC (Emitters) will have stronger motivation than regular, gesture-only-based participants (Users) due to the addition of implicit interaction.

Hypothesis 2. Participants' experience in the Physio and Sham groups will differ on motivation scales. Specifically, the Sham group will have lower motivation ratings compared to participants in the Physio group due to the lack of real-time physiological interaction.

2. MATERIALS AND METHODS

2.1. System Design

In this section, we describe b-Reactable, a DMI that introduces PC to the Reactable system by means of real-time EEG and ECG measures that are associated to tangible objects (physiopucks). Figure 1 offers an overview of the system architecture. In the following subsections, we describe Reactable, physiopucks and their operation, physiological signal acquisition and treatment, sonification, and control strategies.

2.1.1. Reactable and Physiopucks. Reactable is a DMI based on a tabletop interface where tangibles objects (pucks) and hand gestures are used for controlling musical operations [Jordà 2007], as shown in Figure 1. This is done by means of computer vision techniques (reactIVision) that track both fiducial markers and finger gestures on the surface of the interface [Kaltenbrunner 2007] (see Figures 2 and 3).

The Reactable sound synthesis and control methods follow a modular approach, a prevalent model in electronic music, which is based on the interconnection of sound

Fig. 2. A performer playing with Reactable.

Fig. 3. Reactable components [Jordà 2007].

Fig. 4. The two physiopucks added to the Reactable framework. When placed on the tabletop the brain-labeled physiopuck (a) produces an audification of EEG activity based on a white-noise signal. Users and Emitters can change the amplitude of the audification by moving graphic slider that appears on the right side of the puck. The heart-labeled physiopuck (b) drives the BPM of the sound composition according to the heart rate of the Emitter. The BPM values were displayed in the upper right corner of the physiopuck.

generators and sound processors units. In 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, processors (i.e., filters and effects), controllers (which affect the behavior of the generators or processors they are connected to), and global objects (which affect the behavior of all objects within their area of influence). 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 its surface.

Because of this modular approach, the integration of PC features into Reactable is straightforward. Therefore, we created a new version of the interface called *b-Reactable* that added two new pucks (*physiopucks*) to the current Reactable framework. In this new version of Reactable, physiopucks allow performers to use their physiological signals (namely EEG and ECG) to generate sound and control tempo (BPM), in the same manner as using standard Reactable objects (see Figure 4).

2.1.2. *Physiological Signal Acquisition.* b-Reactable allows input from different physiological equipment. In this study we used Starlab's Enobio (neuroelectronics.com), a wearable, wireless electrophysiology sensing system that captures two biosignals: EEG and ECG. It features four channels connected to dry active electrodes at a sample rate of 250Hz.

A dry electrode is placed on the frontal midline (Fz) lobe of participants for EEG recording. Another electrode is placed in the participant's wrist for ECG detection. Physiological signals are acquired, amplified, and streamed wirelessly to the Enobio software suite that applies a band pass filter (centered between 50 and 60Hz) for noise reduction and sends the EEG and ECG data to the sound engine via TCP/IP.

2.1.3. *Sound Engine.* In this study, the choice of sonification strategies has two main motivations. First, we wanted to provide direct sonic feedback on the changes of EEG frequency bands with a minimum of latency. Second, we aimed at a simple, distinctive sonification that would stand out from other sounds generated by Reactable. These guidelines led us to design a sonic interaction based on audification [Hermann and Ritter 2004], an auditory display technique that directly translates data waveform into sound; this is normally achieved by resampling and digitally filtering input values to make them audible. Audification is particularly applied to large datasets with periodic signal components, as in the case of the EEG and ECG (see Våljamäe [2013] for a recent review).

b-Reactable leverages on the already existing Reactable sound engine to generate a direct mapping between EEG frequency bands and the audible sound frequency spectrum. For performers, this sonification appears as a sound generator puck (brain-labeled physiopuck) on b-Reactable. On the other hand, ECG activity is used to control the tempo (beats per minute, BPM) of the interface, appearing as a heart-labeled physiopuck (see Figures 1 and 4). To make it easier for the participants to understand the tempo of the DMI, BPM values were displayed in the upper right corner of the heart-labeled physiopuck.

The sound engine was developed using Pure Data (Pd), a visual programming language for computer music [Puckette 1996]. Pd was 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 was also built with Pd.

2.1.4. *EEG and ECG Signal Processing and Sonification.* In the following, we provide a complete description of the DSP for EEG and ECG data, together with the correspondent sonification and BPM control mappings. Figure 5 shows a diagram of the main building blocks of the EEG sonification and ECG-based BPM control. We processed the signal coming from the Enobio by first applying a DC block filter to contrast the signal drift and then performing a frequency magnitude analysis. Each block was multiplied by a Hann window function of the same size. An FFT with a size of 256 samples is then performed, leading to a spectral resolution of 0.97Hz per frequency bin.

The computed magnitude spectrum for each block is then used to shape the spectrum of a white noise signal. Each frequency bin of the EEG is used to weight the first 128 frequency bins of a 256 bins white noise FFT. Working at 44.1kHz for audio synthesis, we have a covered frequency range going from 0Hz to 11,025Hz, with each audio frequency bin covering about 86Hz. The spectral magnitudes have been equalized by mean of weighting the chosen curve in order to emphasize the weaker higher frequencies.

This straightforward audification approach was used to map dominant EEG activity (mainly alpha band, 8–12Hz) to human audible frequencies. In this manner, the alpha activity, which is known to be associated with activation/relaxation [Wheeler et al.

Fig. 5. Signal processing for EEG sonification and ECG tempo control.

1993], dominated the audification. This allows listeners to hear periodic components as frequencies. As demonstrated by Pauleto and Hunt [2005], through audification, users are able to detect attributes such as repetitive elements, regular oscillations, discontinuities, and signal power to a degree comparable with using visual inspection of spectrograms. The EEG sonification is finally streamed over a TCP-IP/LAN connection to a server running the Reactable software, thus allowing to map it to the physiopucks, the objects that allow direct manipulation of physiological signal audification through hand gestures, and their combination with other Reactable objects (i.e., filters and controllers).

The overall EEG DSP and audification process implied an inherent latency of about 1s. This could represent a problem in case of discrete control of a sound process (i.e., triggers), which would require a maximum latency of 30–50msec. However, higher latencies can be considered as tolerable for a continuous control, as the one applied in our sonification system [Wessel and Wright 2002; Lago and Kon 2004], also given the low-frequency and low-variability of alpha rhythms.

ECG measures were used as a control mechanism to adjust the BPM of the system to the average heart rate of the user. We applied an adaptive rescaling to the ECG signal in order to smooth changes without losing heart rate peak resolution. A 2-second sliding window (500 samples) is used to detect minimum and maximum values, and signal is normalized depending on that sliding window range. Afterward, peaks in the ECG 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% of the normalized range.

2.2. Participants, Experimental Setup, and Procedure

To assess the effect of multimodal control on user motivation, we designed a task-oriented experiment involving two participants working together (i.e., a dyad). We chose this configuration because it allowed us to study how participants perceive their physiology-driven operations during music performance and how a partner perceives implicit interaction involved in the same task.

The experiment took about 45 minutes (equal in all groups) and was conducted in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later revisions. A total of 56 participants were distributed in three groups: the Physio group, where the multimodal system was fully functional; the Sham group, where physiopucks were driven by prerecorded physiological signals; and the Control group, where no physiopucks were present, thus participants were using the conventional Reactable. The Physio group contained 11 dyads, with age mean of 28 ($SD = 3$), 10 females. The Sham group contained 11 dyads, with age mean of 27.1 ($SD = 3.5$), 9 females. The Control group contained 6 dyads, with age mean of 27.7 ($SD = 4.1$), 6 females. Regarding the Control group, it is important to note that, since its dyads were of the same User type, we included 12 participants for comparisons with other four types of participants: *Physio-Users*, *Physio-Emitters*, *Sham-Users*, and *Sham-Emitters*.

2.2.1. The Physio Group. The Physio group involved a pair of participants with two distinct roles: a User, who operated the Reactable in a conventional manner (i.e., controlling pucks with her hands), and an Emitter, who also manipulated the interface through standard pucks and gestures, but with the addition of providing physiological signals for the physiopucks (i.e., EEG audification and BPM controlled through heart rate).

In this way, changes in Emitter's arousal state drove the audification produced by the EEG physiopuck and the tempo was defined by the ECG physiopuck. This means that Emitters were continuously and implicitly controlling. They could also control physiopucks by trying to change their arousal state at will, and through hand gestures (i.e., reducing the volume of the EEG audification). Physiopucks were accessible to both Emitters and Users; therefore, any of them could put them or take them out of the tabletop, or combine them with other Reactable pucks (i.e., filters, controllers).

2.2.2. The Sham Group. Dyads in the Sham group were also composed from User and Emitter pairs. However, physiopucks were not connected to the Emitters' physiological states, but driven by prerecorded EEG and ECG signals. A placebo effect in this group was induced by making Emitters wear the physiological sensors and by telling both members of the dyads that physiopucks were connected to Emitter's EEG and ECG activity.

With the aim of keeping the prerecorded data as close as possible to the physiological signals of a Physio-Emitter, we collected and reused the EEG and ECG activities from a participant working on the same task as the ones applied in the experiment, but during a pilot session. All Emitters within the Sham Group used the same physiological recording.

2.2.3. The Control Group. Participants in the Control group also worked in dyads, but in this case, both participants were Users. Therefore, dyads operated Reactable only through hand gestures, with no physiopucks or physiology involved. These User-User dyads worked with a tempo controller and an additional sound generator that replaced the two physiopucks. This allowed Users to perform similar operations to the ones allowed by the physiopucks. EEG headsets were also placed on both Users, explaining to them that they were used for measurement purposes. In any case, physiological data was connected to the sonification system; headsets were used to create a similar setup to

Table I. Description of the Pucks and Physiopucks Available during the Experiments, According to Reactable Taxonomy, Subtype, and Connections Allowed

Type	Subtype	Connection
Generator	Oscillator	1 audio out N control in
Generator	Sampler	1 audio out N control in
Audio Filter	Delay	1 audio out N control in
Audio Filter	Granular filter	1 audio out N control in
Controller	Sin wave low-frequency oscillator	N control out
Controller	Sequencer	N control out
Global	Metronome	N control in
Generator	EEG Physiopuck for resynthesis	1 audio out N control in
Global	ECG Physiopuck for BPM control	N control out

the other two experimental groups (i.e., wearing and seeing physiological equipment). The Control group performed the same tasks and followed the same procedure as the Physio and Sham groups.

2.2.4. Experimental Procedure. The three experimental groups followed the same procedure, with different dyad composition as described in the previous section. Before starting the experiment, participants were asked to sign a consent form and fill out a pretest questionnaire (see Section 2.3 for more details). Then the physiological sensors were placed on the Emitter's scalp and on the wrist of the nondominant hand, respectively. In order to reduce movement artifacts during ECG acquisition, we asked Emitters to keep their nondominant hand in a resting position or on top of the tabletop interface. In the Control group, EEG headsets were placed on both participants. A testing period followed for about 10 minutes, where electrode impedance and data acquisition was checked. Afterward, all dyads went through a 5-minute explanation session, with the aim of introducing them to b-Reactable and the physiopucks (or the standard Reactable in the case of the Control group). This session included seven Reactable pucks plus the two physiopucks (see Table I), and were the same set of objects available for carrying on the task (see Table II). After the explanation session, dyads had 5 minutes to freely explore the interface through gestures and physiology with the same set of objects. In the Sham group, once the exploration was finished, Sham-Emitters were secretly disconnected from the interface (while keeping the electrodes) to carry on the tasks with prerecorded physiological data.

The experiment included two tasks, each one consisting on the replication of a 15s music excerpt that was created with the same set of pucks that were available to the participants during the test. The tasks also required specific EEG and ECG states, namely high or low level of physiological activation, since the two music excerpts differed in musical pace and audification frequency (see Table II).

First, dyads listened to the music reference. Then dyads had up to 5 minutes to mimic the reference music excerpt. Matching sounds required a concrete combination of pucks and physiopucks, and differed in the activity states required from Emitters (see Table II). The participants could ask the experiment leader to replay the sound reference at any time. The task finished either when the dyads declared to have matched the reference sound, or once the 5-minute period ended. After the task, participants were asked to fill in the posttest questionnaire (see Section 2.3 for more details).

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Table II. Description of Tasks Involved in the Experiment, Including Pucks Involved and a Representation of the Solved Tasks in b-Reactable

	Task 1	Task 2
Description	A fast pace composition that includes a synthesizer (violin) with a modulator for pitch variation, and an oscillator controlled by a step-sequencer. EEG audification generates a high frequency white noise.	A low pace composition that includes a synthesizer (piano) triggering the same note through a step sequencer, and low frequency EEG audification transformed by a granular filter and delay.
Pucks involved
Task Solved	High Physiological Activity	Low Physiological Activity

287 Finally, sensors were removed; participants were debriefed and given a small reward
 288 (chocolate bars).

289 2.3. Measures

290 Demographic information from participants (including music knowledge and famil-
 291 iarity with the Reactable) was gathered through a pretest questionnaire based on a
 292 5-point interval scale. Statements for general music knowledge included “I can play
 293 music” and “I can compose music,” whereas electronic music knowledge included “I can
 294 play an electronic instrument” and “I understand how an electronic music instrument
 295 works.”

296 After each task, we used a posttest questionnaire that included a 9-point bidimen-
 297 sional self-assessment manikin pictorial scale (SAM) for assessment of valence and
 298 arousal [Bradley and Lang 1994], and 11 motivational aspects based on CSCW litera-
 299 ture [Jones and Issroff 2005]. A *Curiosity* measure was added from the attitude scale
 300 of Eagly and Chaiken [1998]. Each of motivation measures is based on one or several
 301 statements to be rated on 5- or 10-point interval scale. The ratings for each measure
 302 were collected through computer-based questionnaires, and the mean was taken if
 303 several questions were corresponding to a specific motivation aspect. Below are listed
 304 motivation measures with an example statement in the questionnaire.

305 **Curiosity (M1):** Task perceived as unusual, example of statement: “Performing with
 306 Reactable was an unusual experience.” 5-point interval scale, 3 questions.

307 **Difficulty (M2):** Rates the difficulty level of the task, example statement: “The tasks
 308 were too difficult to be accomplished.” 5-point interval scale, 3 questions.

Confidence (M3): Self-efficacy on achieving the tasks, example statement: “I’ve accomplished the tasks with efficacy.” 5-point interval scale, 4 questions.

Distribution of Control (M4): Balance of control among subjects, example statement: “I feel I was leading most of the work in every task.” 5-point interval scale, 5 questions.

Social Affinity (M5): Willingness to work together and collaborate, example statement: “I have a relation of friendship with my partner.” 5-point interval scale, 2 questions.

Interface feedback (M6): Measures how multimodal feedback (visual, sound) aids the collaboration between pairs, e.g., “The visual interface of Reactable helped me to understand how to create sound compositions.” 5-point interval scale, 2 questions.

Motivation Time (M7): How does motivation change over time? Does the subject lose interest as time pass by? Example statement: “The first tasks were more compelling and interesting than the latter.” 5-point interval scale, inversed, 2 questions.

Satisfaction (M8): Measures enjoyment and positive attitudes towards the experience, example statement: “Playing with my partner was a positive experience.” 5-point interval scale, 3 questions

Verbal Communication (M9): Measures the importance of verbal communication for solving tasks. Example statement: “Please rate verbal communication according to the importance you think it had during the tasks.” 10-point interval scale, 1 question.

Visual Communication (M10): Measures the importance of the visual feedback provided by the system as a mean of communication with partners. Example statement: “Please rate visual feedback according to the importance you think it had during the tasks.” 10-point interval scale, 1 question.

Gestural Communication (M11): measures the importance of physical manipulation of tangible objects when communicating with partners during tasks. Example statement: “Please rate body gestures of your partner according to the importance you think it had during the tasks.” 10-point interval scale, 1 question.

3. RESULTS

The IBM SPSS v20 software suite has been used for statistical analyses. The alpha significance level was fixed at 0.05 for all statistical tests, and a Greenhouse-Geisser correction was used to compensate for unequal variances [Greenhouse and Geisser 1959]. For multivariate analysis, Wilks’ lambda was used as the multivariate criterion. All variables were normally distributed according to the Kolmogorov-Smirnov test. The reported results were not correlated with participants’ age, gender, or music knowledge indexes, so this analysis is not included in the sections below. For the correlation analyses, an adjusted Pearson’s correlation coefficient Rho has been used to compensate for the small number of observations [Howell 2010]. Since the measures were averaged over several questions, we considered them as continuous variables.

In our analysis, we first ran a one-way ANOVA, comparing all ratings from the four types of participants of the Physio and Sham groups with the ratings from the Control group (i.e., standard Reactable users). Second, leaving out the Control group data, we ran a two-way MANOVA comparing participant’s ratings using two between-subjects factors: “group” (Physio vs. Sham) and participant’s “role-in-dyad” (Emitter vs. User). Third, to study in depth possible similarity between Users and Emitters in dyads, we applied a correlation analysis. Finally, we compared the correlations between participants’ emotional state (SAM scale) and reported motivation aspects.

3.1. Comparing the Four b-Reactable Participant Types to the Control Group

To address our first hypothesis, we compared all four participant types: Sham-Users, Sham-Emitters, Physio-Users, and Physio-Emitters with regular Reactable users in

Fig. 6. Confidence (a), Satisfaction (b) and Gestural Communication ratings (c) across five participant types: the users from the Control group (C), Sham-Users (Su), Sham-Emitters (Se), Physio-Users (Pu), and Physio-Emitters (Pe). Error bars represent SEM values. ***, significance at $p < 0.005$ level; **, significance at $p < 0.01$ level; *, significance at $p < 0.05$ level.

the Control group using one-way ANOVA and two-sided Dunnett posthoc test. From 13 measures, only 3 showed significant changes in the reported motivation aspects.

First, the Confidence ratings showed significant differences among participant types with $F(4, 51) = 3.18$, $p < 0.021$, $h_p^2 = 0.2$ (see Figure 6(a)). From the four participant types, two were significantly higher than the Control group ($M = 2.6$, $SE = 0.2$), both coming from the Physio group: Physio-Users at $p < 0.028$ ($M = 3.4$, $SE = 0.3$), and Physio-Emitters at $p < 0.037$ ($M = 3.4$, $SE = 0.2$).

Second, the Satisfaction ratings also showed significant differences among participant types with $F(4, 51) = 3.57$, $p < 0.012$, $h_p^2 = 0.22$ (see Figure 6(b)). From the four participant types, only Users' ratings were significantly higher than ratings in the Control group ($M = 3.9$, $SE = 0.2$): Physio-Users at $p < 0.038$ ($M = 4.4$, $SE = 0.2$) and Sham-Users at $p < 0.006$ ($M = 4.6$, $SE = 0.2$).

Third, the Gestural Communication ratings also showed significant difference among participant types with $F(4, 51) = 2.89$, $p < 0.031$, $h_p^2 = 0.19$ (see Figure 6(c)). Only Physio-User's ratings ($M = 7.3$, $SE = 0.6$) were significantly higher than in the Control group ($M = 4.8$, $SE = 0.7$), $p < 0.03$. The second highest rating was from Physio-Emitters ($M = 6.7$, $SE = 0.7$), followed by Sham-Users ($M = 6.1$, $SE = 0.6$) and Sham-Emitters ($M = 4.9$, $SE = 0.6$). It should be noted that no significant differences between b-Reactable and Control groups could be seen for the Visual and Verbal Communication ratings.

Fig. 7. The illustration of significant interaction patterns between “group” and “role-in-dyad” factors in the Physio and Sham groups for Motivation (a) and Visual Communication ratings (b) for the Control group (C), Sham-Users (S-u), Sham-Emitters (S-e), Physio-Users (P-u) and Physio-Emitters (P-e). Error bars represent SEM values.

3.2. Comparing Physio and Sham Groups

To address our second hypothesis, all 11 measures of motivation, together with the two SAM scale ratings of valence and arousal were submitted to a multivariate analysis with two between-subjects factors: experimental “group” (Physio vs. Sham) and participant’s “role-in-dyad” (User vs. Emitter).

The multivariate effect of the “group” factor reached significance at $p < 0.044$ with $F(13, 28) = 2.1$, $\Lambda = 0.51$, $h_p^2 = 0.5$. In a posthoc analysis, two measures showed significant differences within this factor, similarly to the analysis in the previous section. First, the Physio group showed significantly higher Confidence levels than the Sham group, $F(1, 40) = 7.7$, $p < 0.008$, $h_p^2 = 0.16$. The corresponding means were $M = 3.4$ ($SE = 0.2$) for dyads in the Physio group and $M = 2.8$ ($SE = 0.2$) for the Sham group (see also Figure 7(a)). Second, dyads in the Physio group also paid more attention to Gestural Communication than in the Sham group, $F(1, 40) = 5.62$, $p < 0.023$, $h_p^2 = 0.12$. The corresponding means were $M = 7$ ($SE = 0.4$) for dyads in the Physio group vs. $M = 5.5$ ($SE = 0.4$) for the Sham group.

The “role-in-dyad” factor reached significance only for the Satisfaction measure. In this case, Users declared higher level of Satisfaction than Emitters, $F(1, 40) = 4.28$, $p < 0.009$, $h_p^2 = 0.157$, in both experimental groups. The corresponding means were $M = 4.5$, $SE = 0.1$ vs. $M = 4.1$, $SE = 0.1$ (see also Figure 6(b)).

Two significant interaction effects between the “group” and the “role-in-dyad” factors also emerged and these response patterns are illustrated on Figure 7. The Motivation Time ratings showed significant differences, with Physio-Users and Sham-Emitters

Table III. The Pearson Correlation Coefficients (and Observations Adjusted Values)

Showing the Consistency within User-Emitter Dyad Ratings

Separate data is shown for Physio and Sham groups (*, significance at 0.05; **, significance at 0.01; and ***, significance at 0.005).

Measures	Physio Rho (Rho adjusted)	Sham Rho (Rho adjusted)
All Measures Together	0.80***	0.71
Arousal	0.25 (–)	0.38 (0.21)
Valence	0.13 (–)	–0.09 (–)
Curiosity (M1)	–0.0 (–)	0.66* (0.61)
Difficulty (M2)	0.36 (0.17)	0.21 (–)
Confidence (M3)	0.92*** (0.91)	0.19 (–)
Distribution of Control (M4)	0.30 (–)	0.54 (0.46)
Social Affinity (M5)	0.44 (0.31)	0.44 (0.33)
Interface Feedback (M6)	0.3 (–)	–0.3 (–)
Motivation Time (M7)	0.59 (0.52)	0.38 (0.22)
Satisfaction (M8)	–0.29 (–)	–0.17 (–)
Verbal Communication (M9)	0.35 (0.15)	0.30 (–)
Visual Communication (M10)	0.67* (0.62)	0.04 (–)
Gestural Communication (M11)	0.24 (–)	–0.25 (–)

declaring significantly more motivation than their partners in the corresponding dyad, $F(1, 40) = 6.61$, $p < 0.014$, $h_p^2 = 0.142$ (see Figure 7(a)). Similar interaction trends could be observed for the Visual Communication ratings with $F(1, 40) = 3.97$, $p = 0.053$, $h_p^2 = 0.09$. Here, same as for the Motivation ratings, Physio-Users and Sham-Emitters were paying more attention to visual feedback than their partners in the dyad (see Figure 7(b)).

3.3. Correlations between User-Emitter Dyad

To complement direct comparisons in Sections 3.1 and 3.2 and to study in depth the collaborative aspects of the experiment, we applied a correlation analysis to evaluate the consistency of the User-Emitter dyads' responses to each measure in the questionnaire (see Table III). When all the questions were combined together, only the Physio group showed a significant level of consistency between participants' responses in User-Emitter dyad. When correlations were analyzed measure by measure, a more detailed picture emerged.

First, the Curiosity measure showed a significant positive correlation within the User-Emitter dyad, but only for the Sham group. Second, the Confidence measure showed a significant positive correlation within the User-Emitter dyad, but only for the Physio group. This is coherent with the results from the previous analysis (Physio dyads showing greater confidence than Sham dyads) and with the results of the role-in-dyad analysis (Emitters and Users showing high confidence ratings in the Physio group). Finally, the Visual Communication measure showed a significant positive correlation within the User-Emitter dyad, but again only for the Physio group.

3.4. Correlations between Motivational Characteristics and Valence-Arousal Ratings

All the results reported in previous sections showed no effects for the participants' SAM ratings of valence or arousal. However, we also decided to check the correlation between these subjective ratings of emotional state and each of the 11 motivational characteristics. Table IV summarizes only the correlations that showed to be both significant and strong/moderate, with the intention of illustrating several recurrent patterns that complement the main findings of Sections 3.1 and 3.2.

Table IV. Significant, Strong and Moderate Correlations between Measures of Motivational and Emotional Experience The adjusted Pearson's Rho is provided for each of the five user types: Control group, Sham-Users, Sham-Emitters, Physio-Users, and Physio-Emitters (*, two-tailed significance at 0.05, **, two-tailed significance at 0.01, ***, two-tailed significance at 0.005).

Measure	Control	Sham-Users	Sham-Emitters	Physio-Users	Physio-Emitters
Arousal (A)		M8, 0.8*** M9, 0.7**		M1, 0.8** M11, 0.6*	M8, 0.6*
Valence (V)		M11, 0.5*	M1, 0.6* M4, -0.5*		M5, 0.7** M7, 0.7** M8, 0.8***
Curiosity (M1)	M11, 0.5*		V, 0.6* M4, -0.5*	A, 0.8** M6, -0.6*	
Difficulty (M2)	M5, 0.7**			M3, -0.8**	M5, -0.7* M10, -0.6*
Confidence (M3)				M2, -0.8** M7, 0.6*	M4, 0.6* M7, 0.6*
Distr. of Control (M4)		M7, 0.6*	V, -0.5* M1, -0.5* M9, 0.8**	M6, 0.6* M11, -0.7*	M3, 0.6* M6, 0.8** M7, 0.6*
Social Affinity (M5)	M2, 0.7**	M6, 0.6*			V, 0.7** M2, -0.7* M8, 0.6*
Interface Feedback (M6)		M5, 0.6*		M1, -0.6* M4, 0.6* M9, 0.6*	M4, 0.8** M7, 0.6*
Motivation Time (M7)		M4, 0.6* M11, 0.7*		M3, 0.6*	V, 0.7** M3, 0.6* M4, 0.6* M6, 0.6* M10, 0.6*
Satisfaction (M8)	M9, 0.6*	A, 0.8*** M9, 0.7**		M11, 0.6*	A, 0.6* V, 0.8*** M5, 0.6*
Verbal Comm. (M9)	M8, 0.6* M10, -0.6*	A, 0.7** M8, 0.7**	M4, 0.8**	M6, 0.6*	M10, 0.7**
Visual Comm. (M10)	M9, -0.6*				M2, -0.6* M7, 0.6* M9, 0.7**
Gestural Comm. (M11)	M1, 0.5*	V, 0.5* M7, 0.7*		A, 0.6* M4, -0.7* M8, 0.6*	

First, Physio-Emitters had the highest number of correlated measures. It is also important to note that, for these participants, pleasant emotional states were associated with Social Affinity, Motivation Time, and Satisfaction scores.

Second, two correlations between measures showed an opposite sign for the Control and the Physio-Emitter group. One was the relation between Difficulty and Social Affinity (see Figure 8). While this correlation was positive for the Control group (adj Rho = 0.7, $p < 0.01$), Physio-Emitters reported higher Social Affinity when Difficulty was lower (adj rho = -0.7, $p < 0.05$). The second relation was between Visual and Verbal Communication. Here, Physio-Emitters had a positive correlation between the two measures (adj Rho = 0.7, $p < 0.01$). On the contrary, the participants in the

Fig. 8. The correlations between Social Affinity and task Difficulty measures for User in the Control group (C, black dots) and Physio-Emitters (P-e, gray dots).

Control group rated Verbal Communication as important while judging the Visual Communication aspects as low (adj Rho = -0.6 , $p < 0.05$).

Third, Emitters and Users in the Physio group had two similar patterns of positive correlation between measures. One of them was between Distribution of Control and Interface Feedback, and the other between Confidence and Motivation Time. Finally, several correlations again highlighted the interaction effects between the “group” and “role-in-dyad” factors for Motivation Time and Visual Communication ratings that were described in Section 3.2 (Figure 7). Both Physio-Emitters and Sham-Users had high positive correlations between Motivation Time and Distribution of Control, and between Arousal and Satisfaction. In addition, Sham-Users shared similar patterns with the Control group: positive correlations between Satisfaction and Verbal Communication, and between Satisfaction and Emotional ratings.

4. DISCUSSION

The results of this study offer a number of insights on the effects of multimodal control (gestures and implicit interaction) in user experience, by measuring multidimensional aspects of participants’ motivation during a musical task. We compared subjective ratings of three groups of participants—the Control, the Physio, and the Sham groups—using Reactable and b-Reactable, a DMI that introduces physiology-based interaction according to EEG and ECG measures. The experiment showed that (1) the motivation brought by b-Reactable significantly differs from the one of the Reactable; (2) the dyads

using b-Reactable had a different motivational experience depending on whether the physiological feedback was real or fake; and (3) Physio-Emitters and Physio-Users had different motivational patterns.

Our first hypothesis postulated that User-Emitter dyads using the b-Reactable system would have a stronger motivation than users of the standard Reactable when performing the same collaborative musical tasks. Eleven motivation dimensions together with valence and arousal pictorial scales were measured through a postexperimental questionnaire. Indeed, several of these measures showed significantly higher ratings for User-Emitter dyads compared to the Users dyads in the Control group. Specifically, Physio-Users had significantly higher ratings for Confidence, Satisfaction, and Gestural Communication than conventional tabletop users. In addition, Physio-Emitters had higher ratings for Confidence and Sham-Users for Satisfaction as compared to the Control group. Importantly, no ratings have been significantly lower than the ones given by Reactable Users in the Control group, showing that b-Reactable and the use of physiopucks do not affect participants' motivation negatively. It should also be noted that the observed effects are most likely caused by the presence of implicit interaction through physiopucks and not due to the unusual experience of using EEG headsets, as participants in the Control group also wore EEG devices. We should also stress the fact that implicit interaction paradigms like the ones presented in this article can also lead to explicit control, with participants trying to alter their EEG and ECG activity to match a given sound or tempo. However, this is more likely to happen after a number of training sessions, and this requires further investigation that goes beyond the current study.

The observed differences between b-Reactable and the standard Reactable could stem from Emitters, who would have a higher level of motivation compared to Users due to a new, implicit communication channel available to them. Indeed, taking a closer look at the differences between the four participant types and the Control group that used the Reactable, we can see that motivation levels of Users and Emitters differed from each other. However, not fully in line with our predictions in Hypothesis 1, Physio-Emitters gave significantly higher ratings only for one measure (Confidence), while the Physio-Users' ratings were significantly higher for Confidence, Satisfaction, and Gestural Communication. In addition, Sham-Users also had significantly higher Satisfaction scores than the Control group. In other words, Users' motivation level in the b-Reactable groups also differed from the Control group. One possible explanation why both Sham and Physio-Users reported the highest levels of Satisfaction, compared to Emitters in the both groups is because Users could only collaborate via hand gestures. Users' operation with physiopucks did not depend on the quality of physiological feedback, real, or sham one, which could be only noticed by Emitters. Furthermore, Users in both groups had a less complex and a more conventional control of the interface. On the other hand, Emitters might not have reached high levels of satisfaction given the expressive limitations of the physiological control and the quality of the audification. Whereas Users had a quite varied repertoire of sound generators to play with, Emitters could have felt tied to white noise audification generated by the EEG-based physiopuck. Perhaps a more pleasant or rewarding sonification would result in better satisfaction ratings from Emitters. As Emitters might not have been able to achieve high expressivity with the provided audification, it would be interesting to explore whether their satisfaction change in the case of other, more complex types of sonifications.

When comparing the differences between the Physio and Control groups, a few issues should also be stressed. First, Physio-Users showed higher ratings of gestural communication, as opposed to the verbal communication preference showed by the dyads within the Control group. Second, social affinity between Physio-Emitters and their partners was highly correlated with reported positive valence. Interestingly, the

Social Affinity ratings were higher when Emitters reported lower difficulty of the task, while an opposite correlation could be seen in the Control group, in which higher scores on difficulty level matched the stronger affinity with the partner.

Our second hypothesis was that the Physio condition would provide a higher level of motivation aspects than Sham, due to dyads perceiving the difference in the feedback quality (i.e., real-time vs. prerecorded). Indeed, the multivariate comparison with all measures combined together showed a significant difference between the two experimental groups. Specifically, two motivation aspects were significantly higher in ratings for the Physio than for the Sham group, namely Confidence and Gestural Communication. This result suggests that implicit interaction could be a relevant technique to enhance quality of collaboration and nonverbal communication during multiuser music performance.

In addition, a significant interaction was observed where Sham-Users and Physio-Emitters showed lower Motivation Time ratings than Physio-Users and Sham-Emitters, respectively. The observed interaction may be explained by two factors: task complexity and the use of Sham recordings. The two tasks differed in complexity, with the second one being more difficult to solve than the first one (as it involved more pucks and deeper configurations). The low Motivation Time measures in Sham-Users could be explained by the challenge that could imply solving tasks with an increasing difficulty with a partner (Sham-Emitter), whose physiology-driven control parameters were not responding according to the Sham-Emitter physiological state (i.e., working with prerecorded EEG and ECG measures). This did not happen in the Physio group, as Physio-Users were collaborating with a partner that had direct control of physiopucks. In the case of Physio-Emitters, solving the second task could have been a significant challenge for them (especially without previous training sessions), thus diminishing their motivation towards the end of the experiment. In sum, this interaction may suggest that it was easier for Sham-Emitters and Physio-Users to solve the tasks, and that was reflected in higher Motivation Time ratings.

The direct between-groups comparisons were complemented by the results from within dyads correlations that showed whether Emitter and User shared similar motivational ratings. The dyads ratings from the Physio group showed high and significant correlations for the Confidence and Visual Communication ratings. This again stresses the fact that Physio dyads effectively collaborated and relied on gestural or visual communication resources rather than on speech. This effect does not mean that there is a tradeoff between communication channels (i.e., more gestural communication, less speech) but a participant preference for one or another. Conversely, Sham dyads' ratings were only correlated for Curiosity measure. Finally, the ratings of Distribution of Control and Interface Feedback, Confidence, and Motivation Time were positively and significantly correlated for both Users and Emitters in the Physio but not in the Sham group. Although we did not address this directly, these results suggest that there might have been some transfer of subjective experience, like confidence or curiosity, between the partners working together at the task.

A specific interaction effect between "group" and "role-in-dyad" factors was also observed, where Users in the Sham dyads and Emitters in Physio dyads had high positive correlations between the ratings of Motivation Time and Distribution of Control, and between the Arousal and Satisfaction ratings. Again, one possible explanation for this result is that Sham-Users and Physio-Emitters had a clearer task compared to their partners in the dyad. In the Sham group, Sham-Emitters perceived and tried to solve the problem with the erroneous feedback, which could explain their high ratings for Visual Communication. Sham-Users in this case were in the control of the situation and reported high levels of satisfaction. On the contrary, Physio-Emitters were the ones who had the most satisfying experience, as shown by the highest number of motivation

measures correlated with positive valence. Taken together, it is clear that the Physio and Sham groups differed significantly on several motivation dimensions.

Both variance and correlation analyses support our second hypothesis and suggest that participants in both groups were able to perceive the quality (real-time vs. sham feedback) of physiological activity displayed audiovisually on b-Reactable. Corroborating this result, the significant correlations of Curiosity ratings for Sham dyads together with their low levels of Confidence can be explained by participants perceiving the Sham feedback from the interface or, at least, having a certain inability to manage the physiological channels. As a sign of coping with this situation, Sham dyads had a high correlation between the Verbal Communication and Satisfaction scores, and the scores of Distribution of Control and Arousal. In sum, the very fact of preferring gestural communication shows the potential of implicit indirect interaction for reinforcing a more intuitive, seamless, and body-centered multiuser interaction.

It should be noted that the fake nature of Sham feedback could be perceived more easily via the audiovisual display of ECG activity. Although we did not assess directly the difference between the perception of EEG and ECG, participants might perceive these two signals differently. Unlike EEG feedback, ECG display was more direct and intuitive (a pulse blasting from the center of the tabletop interface) making it easier to perceive and to compare with the Emitters' own body states. Moreover, the ECG values were displayed in the upper right corner of the physiopuck.

Regarding the validity of our DMI (b-Reactable), the experiment showed that it could be used as a platform for collaborative music re-creation. Previous research on collaborative learning has highlighted that aspects like confidence, social affinity, and distribution of control are of utter importance for increasing learning motivation [Jones and Issroff 2005]. All of these measures have been sensitive to our between-subject manipulation, showing that b-Reactable can increase motivation as compared to standard tabletop systems based on hand gesture control. We also see that aspects like Motivation Time and preference for feedback type (i.e., visual, gestural, verbal) can be used as informative measures when studying participants' motivation during collaborative musical tasks. In our case, the proposed combination of implicit and explicit interaction fostered nonverbal communication and body-centric interactions as compared to gesture-only tabletop system.

When running the experiment, we noticed that almost all participants were surprised and curious about the physiological sensors, even more than about the tabletop system itself. These reactions, together with the fact that the Users' task was not directly affected by the quality of the physiology-based feedback, could account for an increase in User's Satisfaction, keeping their ratings high even within the Sham group. Hence, Satisfaction ratings may have captured a sort of "wow" effect, representing the participant's impression of a "cool" and novel interface. However, it is important to note that while Users themselves were not connected to the system, the fact of being able to use their partners' physiology through physiopucks still made the interface very exciting for them. The lower scores of the Control group, where both partners also had EEG headsets, further support this explanation. Since we are not aware of any other works that use physiology-driven tangible objects in collaborative tasks, many aspects of this unique User-Emitter situation are still to be tested concerning the "anthropomorphic" potential of the physiopucks' concept (e.g., "touching someone's heart"). Other uses of multitouch display may also bring interesting insights about collaborative scenarios based physiology-driven objects, for example, transformation of parallel displays for teamwork, as is it the case of the CityWall public installation by Peltonen et al. [2008].

It should be noted that the effects found in our study might be of temporal nature; thus, future experiments should address the impact of prolonged use of physiopucks. However, it should be noted that this kind of physiology-based interaction is likely

to produce subjective experiences different from gesture-based control. Consider, for example, the BRAAMHS project, a novel musical instrument based on functional near-infrared spectroscopy (fNIRS) that adapts implicitly to users' changing cognitive state during musical improvisation [Yuksel et al. 2015]. As one of the users commented, "I couldn't tell if I was influencing them [patterns] but for some reason it didn't feel random, I don't know why". Finally, our recent work using b-Reactable showed that professional musicians appreciated the use of physiopucks as an expressive control input [Mealla Cincuegrani et al. in preparation; Mealla Cincuegrani 2015].

The presented novel multimodal system, together with the experimental User-Emitter scenario, poses a number of questions on how multimodal display of physiological signals, and its representation through physical objects, may enhance creation and collaboration. Specifically, we believe that future research should aim at explaining the following aspects:

- In which other forms can implicit, physiology-based cues be delivered beyond audification? Should participants always perceive these cues consciously in order to provoke an effect? (e.g., recognizing different levels of excitement from physiology).
- Can the use of the physiopucks lead to a stronger, largely unconscious, interpartner entrainment, synchronization, and anticipation during multiuser collaboration?
- Can the *physiopucks* be perceived as embodied objects?
- Can physiology-driven tangible objects stimulate empathy between participants due to their high level of emotional significance?
- Will the Emitter-Emitter scenario be more effective in terms of motivation than the User-Emitter case?
- What are the expressive possibilities of these multimodal DMIs? What new emotional and collaborative experiences can physiology-based inputs bring to professional musicians?

We envision a number of future improvements to tackle these issues. First, we foresee the implementation of algorithms and signal processing techniques to measure and classify different EEG features (e.g., coherence between specific brain regions or between multiple brains). Second, a multiparameter and versatile sound engine will be needed in order to provide a more flexible, expressive, and configurable auditory display for brain and body dynamics. This sonification software should allow for possible multiple mappings between physiological features and sound, ranging from direct audification to more complex paradigms, such as model-based sonifications [Mealla et al. 2014]. In this regard, the Reactable framework guarantees a straightforward integration of new sonifications into a well-established DMI, facilitating comparative studies. For example, not only brain oscillations but higher-level interpretations like dynamic indices of workload could be then meaningfully sonified [Afergan et al. 2014]. Third, at the methodological level, quantitative measures on music similarity are needed. One option would be to use the similarity measures between the user's compositions and the target sounds, in a way similar to what Serra et al. [2010] employ for musical cover detection. Finally, user entrainment could be studied by exposing participants to their own physiological activity after several training sessions, and synchronization between participants might be detected in multiuser, Emitter-Emitter scenarios.

5. CONCLUSIONS

This article studies whether the use of a tabletop system that support both implicit and gesture interaction (b-Reactable) can affect user motivation in a musical task, compared to the use of a gesture-only tabletop system (Reactable). We compared multiple dimensions of motivation between three experimental groups—Control, Physio, and Sham—using Reactable and b-Reactable with either real or fake physiology feedback.

The experiment showed that the motivation brought by b-Reactable is stronger than the one of the tangible interface just based on gestural inputs in terms of Confidence. On the other hand, the introduction of a fake (Sham) physiological feedback significantly changes Confidence and Communication of participants. Importantly, Physio-Emitters had different experiences than their partners (e.g., in terms of positive emotions and social affinity). These results strongly support the potential of physiology-based interfaces and implicit interaction for improving single-user and multiuser HCI, within or beyond the musical domain. Further developments in this regard could, therefore, explore how implicit interaction could widen multiuser communication, foster user entrainment by perceiving brain and body signals via physiopucks after training, or increase interpersonal synchronization in brain-to-brain interaction.

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Received October 2014; revised October 2015; accepted October 2015