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ABSTRACT

Electronic and digital technologies open immense opportunities for music composition, listening, interaction, and participation. However, at the same time, they critically challenge some of the most basic principles that drive human engagement and interaction with music. This article first presents a theoretical discussion of two of these principles, namely sensorimotor control and participatory sense-making. Thereafter, it presents SoundBikes, a music installation that implements these theoretical considerations. SoundBikes is rooted in the idea that collective music-making is a form of participatory sense-making that emerges from embodied, dynamical and collaborative interactions between co-performers. The core components of SoundBikes include an EMS Synthesizer 100 and two stationary bikes equipped with sensors. To stimulate social interaction and collaboration between cyclist-performers, we designed SoundBikes in a way that performers could exert control over expressive features in the playback of music compositions, by coordinating their (cycling) movements with one another. This functionality is integrated in a gameplay—to further stimulate social

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collaboration and competition—and a visually attractive environment—to provide visual feedback and to create ambiance.

Keywords: art and science; dynamical systems; embodiment; music interaction; new interfaces for music expression; participatory sense-making

Introduction

The development and integration of electronic and digital technologies throughout the twentieth century yielded profound innovations in music composition, listening, interaction, and participation. One of the most radical innovations was technologies that allowed basically any sound to be created through analogue and digital synthesis techniques. This supported and propagated a larger trend in music aesthetics from Late Romanticism onwards to “emancipate” sound and timbre from classical organising principles, leading to a radical new and diverse repertoire of so-called “sound-based music” (Landy 2007). In the process of gaining an immensely rich sound colour palette, however, electronic and digital technologies have critically challenged some of the most basic principles that drive human engagement and interaction with music.

A main goal of this article is to theoretically discuss two of these fundamental principles in more detail, based on the latest insights from musicology and the social and cognitive sciences. In essence, the crux of these principles is that music performance is an active, social, and participatory activity in which sensorimotor control and social interaction are of fundamental importance. As they are related to aspects of expressivity, emotion, agency, empowerment and reward, these principles are commonly considered as main driving forces of people’s motivation to engage with music (Leman 2016). Based on this theoretical discussion, we want to provide a framework from which we can better understand some of the core challenges that electronic and digital technologies impose on music composition, listening, interaction, and participation. In addition, we aim to present a theoretical framework that could guide and stimulate the future design of interactive and participatory music practices mediated by new, emerging technologies. To illustrate this point, another main aim of this article is the detailed presentation of a music installation, called SoundBikes, that implements the discussed theoretical considerations in creating embodied and participatory human interactions using sound synthesis and movement sensing technologies.

Some Historical and Theoretical Considerations Concerning Digitally-Augmented Music Practices

In the early days of electronic and digital music production, specialised sound laboratories and radio studios explored the use of analogue electrical circuitry (Olson and Belar 1955) or digital computers (Tenney 1963) to synthesise sounds. One of the consequences of

this approach was that sound production became detached from real-time (inter)actions and the bodily control of human performers. However, in the first half of the twentieth century, electronic musical instruments had been developed that did allow modest real-time, embodied control over sound synthesis. Prominent examples of such instruments are the theremin, trautonium, ondes Martenot, and solovox, among others. It was only in the second half of the twentieth century though, with the development of the voltage-controlled (VC) synthesiser by Robert Moog, that performers obtained fine-tuned control over electronic sound synthesis (see Moog 1965). VC synthesisers comprised a number of sound generating and processing modules (oscillators, amplifiers, filters, etc.) that could be operated and controlled by so-called external transducers, which translated performers' actions into voltage signals. Such transducers are typically found in the form of keyboards and potentiometers (i.e., knobs and sliders). The main asset of VC synths was their compatibility with conventional musical instruments, such as the keyboard, and hence the possibility to integrate them into traditional forms of musical ensembles. In turn, they allowed the reintegration of embodied and participatory human-interaction aspects into musical performance. However, as Moog anticipated already himself, the challenge at hand was "to investigate, in an objective and systematic way, what transducer configurations will most effectively translate the musician's intent into sound" (Moog 1965, 205). These appear to be "prophetic" words, as they signalled the beginning of the development of a broad art and science community focusing on new instruments for musical expression (cf. NIME community, <http://www.nime.org>). With advances in cognitive, motor control and social sciences, we are now at a point where we have a better understanding of some of the important principles underlying musicians' control over their instruments and the social interaction involved in musical performances. This knowledge may assist in designing better digitally-augmented music practices that afford new forms of musical expression and interaction. In the following section, we discuss two principles related to the knowledge of sensorimotor control and participatory sense-making in more detail.

Principles of Sensorimotor Control in Musical Performance

Important here are sensorimotor processes and mechanisms that relate to prediction and physical effort. These are important as they link to musical expression, emotion, agency, reward and empowerment.

The first important mechanism we argue for involves sensorimotor prediction, in particular related to the transfer of performers' actions into sound (i.e., action-sound mapping). With traditional acoustical instruments, performers' action patterns are to a certain degree (bio)mechanically mediated into sound patterns via the musical instrument. For instance, hitting a drum membrane with full force will result in a loud drum sound with sharp attack. Accordingly, performers easily obtain an intuitive feeling of the causality of the musical instrument; i.e., they can reliably predict the auditory

outcome of their actions. This predictive sensorimotor mechanism is quite powerful and one of the main reasons why people are attracted to play a musical instrument. In his psychological theory of (musical) expectation, Huron (2006) describes prediction as one of the five components that link expectations in music to emotion, motivation, and reward. Importantly, successful predictions may stimulate a sense of agency, referring specifically to the subjective sense of control over actions and their consequences (Moore 2016). Consequently, this feeling of control may lead to strong feelings of pleasure and reward, induced by the activation of the human dopaminergic system (Gebauer, Kringelbach, and Vuust 2012; Zatorre and Salimpoor 2013). Also, the ability to successfully predict the outcome of a planned action allows performers to reliably express their musical ideas and intentions. As such, prediction can be considered the basis of musical expression and social communication (performer-performer and performer-audience communication). The basic problem of digital music production is the fact that the mediation from movement to sound has an arbitrary component, which is due to the fact that the energies of these modalities are transformed into electronic signals. Therefore, the challenge of digital music production is to design action-sound mappings that are intuitive for performers, in order to facilitate (and eventually enrich) musical expression and communication with co-performers and their audience.

A second important mechanism we argue for relates to physical effort and exertion. It is quite common that traditional musical performances—Western and non-Western—demand intense physical effort. Recent research suggests that the strength of (intentional) physical effort a person exerts contributes to his or her sense of agency (Demanet et al. 2013; Minohara et al. 2016). In a study by Fritz and colleagues (2013), it was found that active music making during a strenuous physical activity reduced the perception of physical exertion (compared to a passive music-listening condition). To explain their findings, Fritz and colleagues (2013) formulated the compelling hypothesis that physiological arousal (induced by physical exertion) combined with musical expression is perceived as a strong emotional experience, down-modulating the perception of physical exertion. This may contribute to our understanding of the use of music in cultural practices such as work songs and rituals.

In conclusion, we advocate for the exploration of sensorimotor prediction and physical effort as valuable principles in the design of digitally-augmented musical environments, as they have strong links with musical expression, emotion, agency, and reward.

Principles of Participatory Sense-Making in Musical Performance

Since around the 1990s, under the influence of the so-called “new musicology” movement and ethnomusicological accounts, an important shift occurred in the study of music from a focus on score analysis (formalism) to a focus on musical performance aspects (performative turn) and the reception aesthetics of music (reception and critical theory).

Of particular interest thereby is the different (but, we would argue, complementary) vision of musical meaning. Traditional music analysis has focused rather exclusively on the (symbolic) score and the internal relationships it represents (pitch, motivic, harmonic structures, etc.). From this point of view then, musical meaning is fully encoded within the musical score and the primary function of a musical performance is to reproduce this meaning into audible form. Complementing this formalist approach to musical meaning is the understanding of music and musical meaning from the perspective of the act of the musical performance itself. From that viewpoint, musical performance is a situated bodily practice that creates meaning (Cook 2013; Cross 2013; Fabian 2015). In other words, musical meaning is understood as an active, socially, and culturally constructed process, rather than a pre-composed, static product. We would like to draw attention specifically to musical performance as a social and participatory activity. Social aspects are commonly recognised as main incentives for humans to engage with music, from a performance and reception point of view. The creation of social cohesion is an important function of music, of which the underlying mechanisms are being understood more and more. Research indicates the release of the neuropeptide oxytocin—more commonly known as the hug or love hormone—as the neurobiological basis of the creation of social cohesion through music. Making music together, or dancing together stimulates the release of oxytocin, leading to a reduction of stress and anxiety, and increasing people's sensitivity to social cues (Feldman 2012; Love 2014). Other research, by Gebauer and colleagues (2016), suggested that the release of oxytocin contributes to sensorimotor prediction, which in turn enhances interpersonal synchronisation and cohesion in social (musical) interactions. The creation of social cohesion is important, in particular in relation to musical meaning. In that context, we refer to the concept of “participatory sense-making,” which originated in the work of De Jaegher and Di Paolo (2007). In their enactivist view on social cognition, joint and individual sense-making is strongly connected to how patterns of coordination arise, evolve, break down, and re-occur during social encounters. It relates to the idea that sense-making and creativity emerge at the level of the whole group, through collaborative interaction (cf. Sawyer and De Zutter 2009). In these moments when a group performs as a collaborative “synergistic unit,” performance is optimal and often leads to intense subjective experiences such as flow, empathetic attunement, and altered states of consciousness. Examples of these moments are for example constituted in interpersonal synchronisation and musical groove. Interpersonal synchronisation relates to the temporal coordination of rhythmic movements of two or more people, typically in phase or anti-phase relationships. Groove manifests itself as a propulsive—and often irresistible—feeling of wanting to move to the music, created by small deviations in the timing of repetitive rhythmic patterns. Both interpersonal synchronisation and groove are the result of dynamical interactions between musical gestures and sounds. More, they demonstrate how novel musical qualities, patterns and meaning may emerge at the level of the whole group, not reducible to individual contributions. In traditional acoustical music ensembles across different genres and cultures, such moments where performers collaborate and play

together as a collective unit appear quite frequently, if not specifically targeted. However, in the art and science community working on new interfaces for music expression, this idea of collaborative social interaction and emergent musical phenomena is much less prominent (Maes et al. 2011; Parkinson and Tahiroglu 2013). In the current article, we would like to advocate and promote the development of this idea, from a theoretical and practical point of view. In the next section, we describe in detail a new interactive and participatory music installation called SoundBikes that specifically aimed at stimulating embodied and social collaborative interactions.

SoundBikes, an Embodied, Participatory Music Installation

The Concept of SoundBikes

The starting point of SoundBikes is the basic idea that music performance is an embodied and participatory activity in which sensorimotor control and social interaction are fundamental. Hence, with SoundBikes, we made an attempt to design an embodied and participatory music installation that incorporates the corresponding theoretical principles outlined in the section above. The main components of the music installation are an analogue, voltage-controlled analogue synthesiser EMS Synthi 100 (for sound synthesis) and two stationary bikes equipped with sensor technologies (for sound control). By cycling the stationary bikes, it becomes possible for performers to dynamically control playback parameters of precomposed songs, such as musical tempo, the number of musical layers, filtering, and the spatialisation of the sound. Performers should not have a specific musical background. The application is especially designed in a way that it can be used by a large audience, not necessarily musicians.

Figure 1: Impression of SoundBikes, in action at the opening weekend of De Krook, Ghent, Belgium from March 10–12, 2017

To implement the theoretical considerations above, we paid special attention to how music synthesis parameters could be controlled by performers' actions (cf. action-sound mapping). First of all, we decided on bikes as music controllers as they require physical effort to be operated. For reasons explained in more detail above, we considered this physical effort an important aspect as it relates to musical agency, expression and emotion. Second, based on the available action parameters measured on each of the two stationary bikes—i.e., pedal cadence and weight balance—we selected musical parameters that intuitively matched, namely musical tempo and sound spatialisation. This allowed performers to intuitively predict the effects of their actions on the musical outcome and hence, to reliably express musical intentions. Finally, and most importantly, we explored a new approach to stimulate social collaborative interaction. Our approach to the stimulation of collaborative behaviour is based on principles of reinforcement and reinforcement learning. Reinforcement is closely tied to the concept of reward. Huron (2006) for instance, asserted that positive emotions—such as pleasure and reward—function as behavioural motivators (or, reinforcers), that encourage people to achieve certain, positive states (deemed to be adaptive). Hence, in learning methods that rely on reinforcement principles, people are not instructed explicitly what to do, but a reward (positive reinforcer) is coupled to the desired behaviour and/or a punishment (negative reinforcer) coupled to unwanted behaviour. It is assumed then that people will be “attracted” to exhibit the desired behaviour, as they receive a reward in turn. In the case of SoundBikes, the desired behaviour is social collaborative interaction, with a specific focus on joint synchronisation. To “seduce” people to jointly synchronise their bike riding and corresponding sounds—and thus to collaborate socially—we added three types of reward to the design of SoundBikes. The first type of reward was a musical reward, related to the idea of emergent musical qualities; i.e., an extra melody and bass were received when jointly synchronising. The second type of reward was a sensorimotor reward, related to the idea of sensorimotor alignment; i.e., musical patterns and action patterns become aligned when jointly synchronising. And the third type of reward was related to a game-challenge.

The practical details of the action-sound mapping strategies are thoroughly discussed in the section “Action-Sound Mappings.” Next to collaborative musical control and interaction, we added appealing visual displays and a game to make of SoundBikes an integrated multimodal experience (with a focus on music however). The game and the action-visual mapping strategies are discussed in the sections “Game” and “Action-Visual Mapping” respectively. Finally, in the section “Evaluation Study,” we present an evaluation study to test the ability of SoundBikes to stimulate musical interaction and collaboration.

Action-Sound Mappings

For SoundBikes, the Belgian electronic music and rock band Soulwax (<http://soulwax.com>) created three electronic (dance) compositions using the EMS Synthi 100 synthesiser (a voltage-controlled analogue synthesiser from 1971). Each composition was completely made from sounds and sound sequences synthesised by the EMS Synthi 100 and recorded by a computer using Ableton Live. For each composition, recorded sounds and sound sequences were edited in Ableton Live, and vertically arranged across multiple audio tracks and horizontally along a timeline. Each composition contained 64 bars (with 4 beats per bar). For the playback of the compositions, we used an 8-channel audio output routed to a speaker array of eight speakers. Four of these speakers were placed in a line behind the two bikes, two of them in a line to the left of the bikes, and two of them in a line to the right of the bikes (see Figure 1). In addition, we had a subwoofer for the low-pitched audio frequencies.

The core idea of SoundBikes is that a composition can be played by two performers by cycling the stationary bikes. On each bike, we measured two bike parameters, namely circular pedal crank position (expressed as an angle from 0 to 360°) and body weight balance (where “maximal weight to the left” to “centre” to “maximal weight to the right” were represented in continuous values from -1.00 to 0.00 to +1.00). These bike parameters were used as real-time and continuous control signals for manipulating expressive musical synthesis and playback parameters of the composition. What was particular to SoundBikes was that musical parameters were not controlled by individual bike parameters, but rather by collaborative, joint coordination—in particular joint synchronisation—patterns of both bikes’ parameters. Hence, performers had to work together in order to control the music expressively. As explained above, collaboration was stimulated by different types of reward. In the following sections, we discuss in more detail the joint coordination patterns that were used as control signals to manipulate musical synthesis and playback parameters.

- *Average tempo*: From the circular crank position signals, we calculated the number of rounds per minute (RPM) for each bike. The RPMs from the two bikes were averaged, and this value was used as real-time control signal for setting the global tempo of the playback of the composition in Ableton Live. Hence, when the two performers managed to ride with the same pedal cadence, both of their cadences were synchronised also to the musical tempo, which was expected to give a pleasant feeling (cf. sensorimotor reward).
- *Phase consistency*: The phase is defined as the difference in circular crank position between the two bikes, expressed as an angle (in °). At the start of every new round of one of the bikes, we calculate the difference in phase angle with the other bike. This angle is represented as a phase vector on a unit circle. From the last five detected phase vectors, we calculate the corresponding resultant vector length,

leading to a value between 0.00 (complete random phase relationship) and 1.00 (complete consistent phase relationship), indicating the phase consistency of the pedal coordination pattern of the two performers. This value is used to control the volume of the subwoofer channel and of a melody layer in the musical composition; 0.00 means volume is maximal down, 1.00 means volume is maximal up in a way that fits the composition as intended by the composers. Hence, if performers collaborated and aligned their pedal cadence, they received a musical reward in the form of extra bass and an extra melody in the composition (cf. synergy idea).

- *Average body weight balance:* We calculated the average of the bikes' individual body weight balance signals continuously and in real-time, which resulted in a signal, ranging from -1.00 to +1.00. The goal was to reflect the averaged weight balance in the positioning of the sound along the array of eight speakers (cf. spatialisation). This means that when both performers lean to the left, sound will come from the left speakers. If they shift their weight from left to right, the sound will accordingly move along from the left to the right over the speaker array. Hence, similar to their pedal cadence, when swaying their bodies together from side to side, their movements will be coordinated with one another and, with the spatialisation effect in the music playback. Again, this was expected to function as a musical reward, stimulating social coordination and collaboration.

Game

The above described action-sound mappings were integrated into a game design. The game was meant as an additional strategy to stimulate performer-cyclists to interact and collaborate. In the game, the basic goal for the performers was to cycle along a specified trajectory pattern (see Figure 2). The cyclists' position along this trajectory corresponded with the timeline of a composition, which was defined in bars and beats. As the performers had control over the global tempo of the music playback (see above), they could progress faster or slower through the timeline of the composition, and correspondingly through the trajectory pattern.

Throughout the process of moving forward through the trajectory (and hence the musical composition), performers received specific instructions on how to manipulate musical features, based on the action-sound strategies explained in the section above. To allow some variation, the total trajectory (and hence the musical composition) was subdivided into four consecutive parts, in a way that all parts contained an equal number of bars (i.e., 4 times 16 bars). From the first to the third part, performers were instructed respectively to synchronise their pedal cadence with one another, to continuously synchronise their body sway from left to right, and finally, to both synchronise pedal cadence and body sway. In these parts, apart from controlling the global tempo and/or spatialisation of the music, the additional effects of adding extra bass and an extra melody (described

in “Phase Consistency”) were added. In the fourth part—the “sprint-to-the-finish” part—an aspect of competition between the two performers was introduced as they were instructed to ride as fast as possible. In this part, the fastest of the two performers took control over the global tempo of the music. Apart from the effects on the musical playback, the performers could earn points as an additional motivation to mutually interact and collaborate. In parts one to three, the score was the accumulated sum of the performers’ phase consistency that was measured every beat. In part four, we rescaled the tempo of the fastest rider, ranging from 50 to 150 RPM, to a range from 0.00 to 1.00, and we accumulated the score with this value, on every beat. As is typical for many games, the goal of SoundBikes was to score as many points as possible, together.

To give instructions to the performers and the audience, as well as to make the game more visually appealing, we provided additional visual feedback, discussed in more detail in the following sections.

Action-Visual Mapping

SoundBikes incorporates visual displays consisting of interactive multi-screen projections, remote screens on the bikes and immersive atmospheric lights. The main purposes of these are to provide information, inspire collaboration and competition between performers, and to create an immersive experience. For the audience, game progress was visualised on a screen of 8-by-2 meter, placed behind the participants. The visuals displayed game progress and scoring information (see Figure 2). For the participants, additional screens were added on each bike to provide individual interactive feedback (pedal cadence, weight balance, game progress, and the score) as well as task descriptions to both participants (see Figure 3). For atmospheric lighting, 14 digital multiplexed (DMX), multicolour light-emitting diode (LED) fixtures were used. All lights were interactively controlled based on the gameplay, music and current process. For instance, the intensity of the lights increased and decreased in synchrony with individuals’ pedal cadence or the beat of the music. Also, lights indicated the colour of the bike they were aiming at (red or blue). In addition, colours morphed to green when high instant synchronisation scores were detected.

Figure 2: Visual feedback presented to the audience

Figure 3: Visual feedback presented to the performers, using a smartphone

On the left of Figure 2, the trajectory pattern that performers had to ride through is displayed. The graphics design was based on the logo of the venue (De Krook, <http://dekrook.be>) where SoundBikes was released from March 10–12, 2017. In addition to the trajectory pattern, RPMs and body weight balance were displayed, together with the performers' phase consistency. On the right (Figure 2), the visual display shows performers' phase consistencies (per beat) plotted over time, together with their global score.

Evaluation Study

Design

To evaluate the ability of SoundBikes to stimulate musical interaction and collaboration we integrated SoundBikes into an evaluation study. For that purpose, we presented SoundBikes during the opening weekend of De Krook from March 10–12, 2017 (<http://dekrook.be>). This was a public event that attracted about 20 000 visitors. The SoundBikes installation was setup in a dedicated space with dimensions 10-by-10 m, and a height of 7 m (see Figure 1). Visitors could enter the room and freely form couples to perform SoundBikes on stage. While performing, other visitors could listen to the performance. In this way, we created a quite realistic performance situation in which SoundBikes could be tested. In total, we obtained data of 81 participating couples.

Analysis

During the participants' performance, we collected data throughout the four parts of the game. At each musical beat, we calculated the couples' phase synchronisation (see "Phase Consistency"), balance synchronisation (see paragraph "Average body weight balance"), and tempo synchronisation. Tempo synchronisation was measured as the difference in RPM, calculated as the minimum RPM divided by the maximum RPM. This led to a score ranging from 0 to 1, with one as perfect synchronisation and all other values, if multiplied by 100, representing the difference in RPM expressed as a percentage with respect to the maximum RPM. On the basis of these three scores, we could evaluate the participants' performance in terms of interaction and collaboration with respect to the instructions given throughout the four different game parts (1=sync pedal cadence; 2=sync body sway; 3 sync pedal cadence + body sway; 4=sprint as fast as possible).

For each of the three scores, we performed a Friedman test (as normality of the data was violated) to check for differences between the four parts of the game. Significant differences were followed up by posthoc tests, consisting of pairwise comparisons between all game parts, using Wilcoxon signed-ranked tests, with a Bonferroni-corrected significance level ($.05 / 6 = .0083$). A visual representation of the average score profiles across the four game parts is given in Figure 4.

Results

- *Phase synchronisation score.* A Friedman test indicated a significant difference between the scores of the different game parts, $\chi^2(3) = 30.69$, $p < .001$. Posthoc analyses demonstrated a significant difference between part 1 (Mdn = .73) and part 2 (Mdn = .59), $z = 3.07$, $p = .002$, $r = 0.24$, between part 1 and part 4 (Mdn = .53),

$z = 5.64, p < .001, r = 0.44$, and between part 3 (Mdn = .68) and part 4, $z = 3.57, p < .001, r = 0.28$.

- *Tempo synchronisation score.* A Friedman test yielded a significant difference between the scores of the different game parts, $\chi^2(3) = 18.22, p < .001$. Posthoc analyses indicated a significant difference between part 1 (Mdn = .88) and part 4 (Mdn = .83), $z = 3.52, p < .001, r = 0.28$, part 2 (Mdn = .88) and part 4, $z = 3.92, p < .001, r = 0.31$, and part 3 (Mdn = .90) and part 4, $z = 4.69, p < .001, r = 0.37$.
- *Balance synchronisation score.* Again, we found a significant difference between the scores of the different game parts, $\chi^2(3) = 57.13, p < .001$. Posthoc analyses indicated a significant difference between part 1 (Mdn = .10) and part 2 (Mdn = .14), $z = 4.81, p < .001, r = 0.38$, part 1 and part 3 (Mdn = .16), $z = 5.35, p < .001, r = 0.42$, part 1 and part 4 (Mdn = .16), $z = 6.51, p < .001, r = 0.51$, part 2 and part 4, $z = 4.41, p < .001, r = 0.35$, and part 3 and part 4, $z = 3.04, p = .002, r = 0.24$.

Figure 4: A visual representation of the average score profiles

Figure 4 offers a visual representation of the scores for phase (red), tempo (green), and balance (blue) synchronisation, averaged over all couples ($N=81$), and with scores calculated for each beat; that is 4 (parts) $\times 16$ (bars) $\times 4$ (beats), equalling 256 beats. Per game part, the average overall beats (16×4) is represented (black dots) with corresponding error bars representing standard errors of the mean. Statistical significant differences between game parts are indicated by: * $p < .05$, ** $p < .01$, and *** $p < .001$ (corrected for multiple comparisons, using the Bonferroni method; p / number of comparisons).

Discussion

Looking at tempo synchronisation, we can observe that, at the beginning, both participants had their own pedal cadence, which is reflected in a relatively low tempo synchronisation score. However, throughout the first part of the game, one can notice a steep increase of tempo synchronisation, indicating the effectiveness of the game instruction, namely to synchronise pedal cadence with one another. Once participants “found” each other, tempo synchronisation remained relatively stable until the fourth part, where the instruction was to sprint as fast as possible. The significant drop in tempo synchronisation indicated that interpersonal collaboration was effectively disrupted by the game instruction, and participants rode each for themselves.

Phase synchronisation is a more detailed measure of interpersonal synchronisation that looks at how participants exactly synchronise the angle (i.e., circular position) of their pedal crank with one another. Similar as to the tempo synchronisation score, one can notice a steep increase in phase synchronisation score throughout the first game part. Interestingly, when participants are asked to synchronise their body sway, in the second game part, they lose phase synchronisation as a consequence. Then again, in the third part, one observes an increase of phase synchronisation, followed by a significant drop when collaboration was disrupted and participants were asked to sprint to the finish at their own tempo.

Concerning balance synchronisation, the results show that the instruction to synchronise body sway effectively increased the respective score. However, the most noticeable observation in general is that balance synchronisation seemed to increase gradually but continuously throughout the four successive game parts. Also, results indicate that the participants in general had much more difficulty synchronising their body sway compared to synchronising their pedal cadence.

In general, these results suggest that SoundBikes is effective in stimulating embodied and social interaction and collaboration, as evidenced by specific patterns within tempo, phase, and balance synchronisation profiles. These results are encouraging, especially given the context of presentation in which visitors could freely and ad hoc explore SoundBikes without much background or preparation. In the future, more controlled

and long-term experiments will be designed to go into more detail. Also, next to a focus on measured interaction patterns, it would be of interest to assess more qualitative aspects, related to motivation, pleasure, and musical aesthetics.

Conclusion

New technologies for sound production, playback and (embodied) control have allowed new forms of musical expression, interaction and communication to emerge. In combination with other media and augmented reality applications, exciting multimodal and immersive environments can be created. In the current article, we argued that reliable sensorimotor control and participatory sense-making are important principles that may enrich social interaction in and with these environments. After a historical and theoretical consideration of these principles, we introduced SoundBikes, a music application that specifically aimed at stimulating embodied and social collaborative interactions. The most innovative aspects of SoundBikes were the integration of physical effort as an important performance parameter (therefore the use of bikes), and a focus on collaborative interaction, two aspects that have been little explored in new interfaces for musical expression.

In design, SoundBikes was meant as an implementation of the broader theory of participatory sense-making as articulated in the domain of social cognition (De Jaegher and Di Paolo 2007). This theory points to the importance of dynamical (cf. emergent, self-organising) interaction and co-creation processes in social understanding and organisation. In that regard, the theory of participatory sense-making fits into the broader (dynamical) systems theory that studies organisation principles in diverse natural, social and biological phenomena. In SoundBikes, the whole system, including the interdependencies between its components, was designed in order to stimulate participatory interaction, and to let novel musical qualities emerge from this interaction. We focused thereby on joint synchronisation as a type of social interaction. However, in future work, it would be worthwhile to explore more types of social interaction and coordination (e.g., entrainment, turn-taking, imitation, reversing, etc.). Apart from exploring types of social interaction, also valuable would be to investigate how people can be motivated to effectively interact socially. In SoundBikes we explored a reward-based approach. One of the concepts that was explored was the concept of “synergy,” indicating the formation of novel musical qualities that emerge from the interaction itself. In SoundBikes, we included this idea by adding melodic lines or extra bass when people jointly synchronised. It would be worthwhile to elaborate on this idea by adding different forms of synergy (e.g., groove). Finally, it would be valuable to explore designs that allow interactions not only to arise, but also to change and evolve over time, in order to create truly dynamical and open-ended musical environments (de Valk, Bekker, and Eggen 2015).

From a scientific point of view the development of digitally-augmented artistic environments and practices is also highly interesting, specifically from a digital humanities' perspective. With this term, we want to point to how new artistic practices may provide "real-life" settings that could be studied to increase our knowledge of principles underlying human interaction, organisation, and participatory sense-making in music. Accordingly, the relationship between artistic creation and scientific knowledge is one that could be mutually reinforcing, allowing innovative and cooperative dynamics to be created between the arts and (interdisciplinary) sciences. SoundBikes is an example of such a setting, where art and science meet. In our opinion, it would be worthwhile to develop this approach further in more systematic ways in future work.

In the process of investigating the underlying dynamics of people's motivation to engage with music, this study exposes the unsolved problematic relation between research work, artistic work, and documentation. Reproducibility is one of the cornerstones of the scientific methodology. But an increasing number of studies, such as the present one, make use of installations with a strong digital-technology component for their observations. Accurately reproducing these setups is self-evidently very difficult, and very expensive. One way to compensate this limitation, while striving to keep the quality of the scientific methodology intact, is to include a detailed description of the technological setup in the research report, as it has been done in this article. The degree of granularity of the description may vary from case to case, but the irreconcilable relation between the obligation to be able to reproduce an experimental setup and the fact that currently used setups are often too complex to be exhaustively described, needs to be taken in consideration consciously in order to preserve the "transparency and accountability of research processes" (Levin et al. 2016, 129).

At the same time, this state of things is refractory to the preservation of scientific data, a very important topic in the scientific world today (Open Science: Open Access and Open Data). Europe has made a definitive choice for open access by 2020,¹ a very ambitious goal where "re-use" is a key concept and it means that data must be "useful rather than simply available" (Levin et al. 2016, 133). Scientific data is often structured (e.g., data captured by sensors), which in many ways makes the preservation task easier, but it also includes software and simulations that need to be annotated, and "highly specialized documents reporting the researchers' work and conclusions" (Barateiro et al. 2008, 388). SoundBikes moves in this direction, leveraging on the strong connections that the research team has in a wide international network, and participating in the experience of an ongoing research project on the documentation of artistic interactive installations with a strong digital-technology component (Bressan 2017).

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1 See <https://www.politico.eu/wp-content/uploads/2016/05/NLOpenaccess.pdf>

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