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The BeatHealth Project: Application to a Ubiquitous Computing and Music Framework

Joseph Timoney, Maynooth University, Maynooth, Ireland

Sean O'Leary, Maynooth University, Maynooth, Ireland

Dawid Czesak, Maynooth University, Maynooth, Ireland

Victor Lazzarini, Maynooth University, Maynooth, Ireland

Eoghan E. Conway, Maynooth University, Maynooth, Ireland

Tomas E. Ward, Maynooth University, Maynooth, Ireland

Rudi C. Villing, Maynooth University, Maynooth, Ireland

ABSTRACT

This work will elaborate on the new EU Beathealth project: an initiative to create an intelligent technical architecture capable of delivering embodied, flexible, and efficient rhythmical stimulation adapted to individuals' motor performance and skills for the purpose of enhancing/recovering movement activity. It will then explain how it can exemplify the principles of Ubiquitous Music and how knowledge from this field can suggest creativity-driven social enhancements. Case Studies will be presented to illustrate potential applications and additionally a short discussion on suitable theoretical guidelines will be made.

Keywords: *Biomedical Mobile Technology, Entrainment, Music Synchronisation, Music Technology Applications, Wearable Sensors*

INTRODUCTION

In recent times scientists have begun to seriously investigate how rhythm and music can be harnessed as a drug-free way of stimulating health (Pollack, 2014). Music affects our autonomic nervous system activity, stimulating sensations of wellbeing at a subconscious level (Ellis & Thayer, 2010). This has naturally led behavioural scientists to posit that this could be a source of inspiration for a whole new set of therapeutic tools. Innovations in mobile technology in the last 10 years offer a very promising means by which such therapies can be delivered whenever the user or patient is free to practice them, and wherever they happen to be.

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The collaborative research project 'BeatHealth' has been conceived to be at the forefront of these technological developments (BeatHealth Consortium, 2014). The objective of the project is to create a new method for improving health and wellness based on rhythmic stimulation. The system under development is an age-friendly, portable system that has the capability to invigorate the user through musical playlists and then simultaneously record their physiological activity (i.e., during walking or running) via advanced sensors. Currently, the music playlists are built using commercial audio tracks; these are employed so that users can increase their motivation by using music selections that they enjoy. The sensors have been custom-built to capture the individual's motor performance and physiological response. Additionally, as the kinematic data and stimulation parameters are collected on the fly they are to be recorded via a dedicated network-based e-Health application for storage on a cloud service. This will facilitate the visualization of information on movement performance for the individuals themselves and for sharing among family members, doctors and coaches. Such access to this information will empower the user to have greater awareness of her/his motor condition, whether healthy or deficient, and encourage them to adopt a more active lifestyle to either enhance their performance or compensate for a motor disorder they might have.

An essential component to this application is the delivery of the music used to stimulate the kinematic activity. It is not simply a playback mechanism; instead it takes a significant role in the process. The belief is that by encouraging an entrainment, or synchronization, between the music and the movement then the maximum benefits should be obtained for the user. This can be realized at both a coarse and fine degree; from simply choosing music whose tempo is close to the rhythm of movement up to using special audio processing techniques to dynamically adapt the beat pattern of the music to align itself exactly with specific landmarks in the user's movement.

The idea of synchronizing music for sports training has been around for some time. (Terry & Karageorghis, 2006) reported that anecdotally it is known that synchronous music can be applied to aerobic and anaerobic endurance performance among non-elite athletes and exercise participants with considerable effect. As well as running, it has also been considered for application to cycling, rowing and cross-country skiing (Karageorghis & Priest, 2008). However, the severe limitation of a standard commercial portable music player is that the onus is on the person to adapt to the music under all circumstances. Significant recent developments in mobile computing power have ushered in new ideas for applications where the music can interact dynamically with the user's activities leading to a more stimulating interaction. Earlier systems adopting this concept for running have been described in the research literature by (Elliot & Tomlinson, 2006), and by (Hockman, Wanderley & Fujinaga, 2009). The BeatHealth project itself is an evolution of the D-jogger application (Moens et al., 2010). Rowing was shown too to benefit from technological assistance (Schaffert 2009). Commercially, the first product that could adjust its music playback in response to movement was first introduced by Yamaha as the BODiBeat (2007), followed by PhilipsActiva (2010). Both devices use a traditional interface and are focused on simply selecting tempo-appropriate music to optimize workout performance. A number of mobile phone apps such as Nike+ (Nike+, 2015) and Runkeeper (Runkeeper, 2015) have been released more recently. However, in all cases unfortunately the relationship between the runner and the music is not one of a seamless synchronous interaction throughout the activity. It is worth noting too that only very recently has a similar commercial application appeared for people with Parkinson's disease (BeatsMedical, 2015), but its solution is unsophisticated in comparison to what BeatHealth can offer. Thus, there has been a strong case for developing the BeatHealth approach that will provide a stronger and more personal interactivity between the music and movement, resulting in improvements in both the user performance and enjoyment.

Although not specifically being a music making application, the integration between music and computing in the 'BeatHealth' project means that it can be related to a branch of the research field of Ubiquitous Music Systems, see (Keller et al., 2014). This discipline has received much attention in recent years (UbiMus, 2010-2015). According to (Pimenta et al, 2009) these systems should support mobility, social interaction, device independence, and context awareness. The proposed framework of 'BeatHealth' satisfies these criteria. Additionally, in establishing such a connection, ideas from Ubiquitous Music systems can inspire tangential developments for the BeatHealth platform that could expand its capabilities, thus broadening its user base. The remainder of the paper aims to investigate this more fully. Firstly, some background to Ubiquitous computing is given combined with a short explanation of Ubiquitous music systems. Some detail on the scientific conceptual framework behind 'BeatHealth' is then provided, followed by an outline of the technological architecture. These will be covered in Sections 3 and 4 respectively. Section 5 will discuss the relationship between 'BeatHealth' and Ubiquitous Music systems. Section 6 will discuss some considerations necessary prior to developing BeatHealth for this discipline followed by three potential applications given in the form of Case Studies. Finally, Section 7 will provide some conclusions to the paper.

UBIQUITOUS COMPUTING AND MUSIC

Following mainframe and personal computing, Ubiquitous computing, also known as 'Pervasive computing', is considered to be the third wave of computing technology (Moloney, 2011). The underlying idea is that as technology improves, devices become smaller but with an increasing power such that they can be imperceptibly embedded in the general environment, thus delivering ubiquitous access to a computing environment (Moloney, 2011). A goal of such technology is to simplify people's lives using context aware algorithms that can self-adapt, responding to users' needs. The five key components of ubiquitous computing systems have been determined as (Kurkovsky, 2007): (1) Embedded and Mobile Devices (2) Wireless Communications (3) Mobility (4) Distributed Systems and (5) Context Awareness and Invisibility. Ubiquitous computing integrates a broad range of research topics, which includes, but is not limited to, distributed computing, mobile computing, location computing, mobile networking, context-aware computing, sensor networks, human-computer interaction, and artificial intelligence. Although the initial incarnation of ubiquitous computing was in the form of "tabs", "pads", and "boards" (Weiser, 1991) built at Xerox PARC from 1988-1994, it has come through a revolution with the advent of the mobile smartphone. This facilitates a Ubiquitous computing that is "invisible, everywhere computing that does not live on a personal device of any sort, but is in the woodwork everywhere" (Weiser, 1991). The mobile phone has now become a true manifestation of the pervasive service and has become natural for the majority of users to conceptualize and interact with (Roussos, Marsh, & Maglavera, 2005).

Ubiquitous music is a research area that is a subset of ubiquitous computing featuring mobile and networked music, eco-composition and cooperative composition. A ubiquitous computing music system can be defined as a musical computing environment that supports multiple users, devices, sound sources and activities in an integrated way. Such technology allows for mobility, social interaction, device independence, and context awareness (Pimenta et al., 2009). However, a Ubiquitous music system places strong demands on the computing interface. A good example is the use of mobile devices. Depending on the desired activity, there may be needs beyond the screen interface requiring context awareness mechanisms and the configuration of location-specific parameters. These then necessitate that sensor or actuator capabilities must be included with the system. The major benefit of the Ubiquitous computing platform for music is that it can empower both non-musicians as well as musicians to express themselves through the medium of music in a collective, open-ended manner that enhances feeling of cooperation, creativity and solidarity.

THE THEORY AND SCIENCE OF BEATHEALTH

Appreciation of musical rhythms is an important feature of human culture. A key feature of rhythm is an underlying regular beat: a perceived pulse that marks equally spaced points in time (Cooper & Mayer, 1960), (Lerdahl & Jackendoff, 1983). Humans have an innate ability to couple movement to external rhythms. Moreover, while humans share rhythm perception (or duration-based timing) with other primates, the skill of beat induction (or beat-based timing) is only present in humans and a select set of bird species (Honing et al., 2012). Newborn infants can detect the beat in music so it appears that the capability of detecting beat in rhythmic sound sequences is already functional at birth (Winkler et al., 2009). Beat perception generally feels to be automatic and the majority of the adult population can easily sense it (Drake, Penel, & Bigand, 2000); the ability to engage in dancing being an obvious example. This ability occurs without musical training and can commonly be seen in young children. Neuroimaging has confirmed activity in "motor areas" of the brain during the production and perception of rhythm (Schubotz, Friederici, & von Cramon, 2000), (Danielsen et al, 2014). Thus, moving to the beat of an external auditory stimulus is sustained by a dedicated neuronal circuitry including subcortical areas, such as the basal ganglia and the cerebellum, and cortical regions (that is, the temporal cortex, prefrontal areas, and the Supplementary Motor Area) (Repp & Keller, 2008), (Zatorre, Chen, & Penhune, 2007). The basal ganglia in particular show a specific response to the beat during rhythm perception, regardless of musical training or how the beat is indicated.

A natural extension of these findings to applied research is to exploit rhythm as a way to enhance movement performance. Rhythm, by its tendency to recruit regions of the brain involved in motor control and timing (Zatorre, Chen, & Penhune, 2007), (Grahn & Brett, 2007), and by fostering synchronized movement, is ideally suited for modifying and improving movement performance (e.g., increasing movement speed or frequency or reducing variability). It is worth noting that the basal ganglia are compromised in people suffering from motor disorders, for example Parkinson's disease, and patient studies have shown that they exhibit deficits in timing tasks (O'Boyle, Freeman, & Cody, 1996). However, rhythmic signals with a strong external beat have been observed to ameliorate gait problems in persons with Parkinson's disease (Nombela et al., 2014).

Entrainment and Self-Entrainment

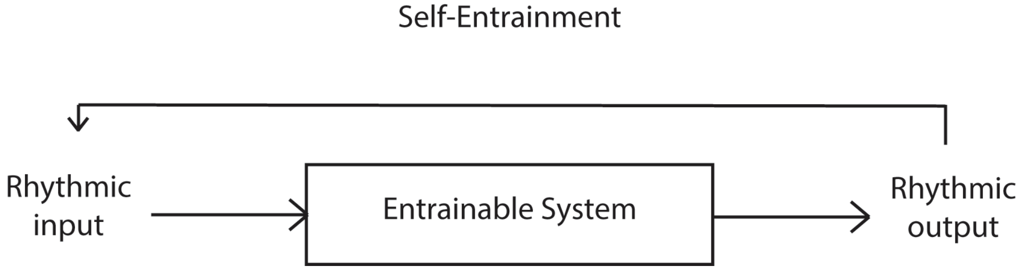
This link between an external rhythm and the human body's movement response is a phenomenon known as *entrainment* (Clayton, Sager, & Will, 2004). This concept describes the synchronicity of two or more independent rhythmic processes. Huygens is credited with being the first person to identify the phenomenon of entrainment (Clayton, 2012). Entrainment among the limbs of an individual has been well studied, as for example in the study of gait or finger movement (Kelso, 1995). The basic dynamics of two independent but coupled body parts can be modelled with the help of a simple mathematical equation that bears his name: the Haken-Kelso-Bunz (HKB) model (Haken, Kelso & Bunz, 1985). More recent work by (Jantzen, Steinberg & Kelso, 2005) using MRI observed an entrainment specific effect, where participants were asked to make finger movements after being entrained to a rhythmic stimulus train, either in synchronization mode (in phase) or syncopation mode (antiphase) with an auditory metronome.

Among its many applications entrainment also appears as a topic in music research and is best illustrated in its use in the study of musical meter. An element of meter is the 'beat': this is a perceived emphasis of certain events or pulses within it that are equally spaced in time. (Trost et al, 2014). A current model under study by music psychologists is the Dynamic Attending Theory (DAT) that focuses on the role of metrical structure as an active listening strategy (Bolger, Trost, & Schön, 2013). Essentially, rather than assuming that the perception of time and meter are solely determined to be within the musical cues transmitted from performer to listener, this model proposes that rhythmic processes endogenous to the listener entrain to cues in the musical sound. This entrainment model appears to better reflect the cognitive processes than others (Bolger, Trost, & Schön, 2013). It has also been suggested that the entrainment concept can be used to study the proto-musical behavior in infants (Bolger, Trost, & Schön, 2013).

Not all entrainment involves an external stimulus, either environmental or inter-personal. 'Self-entrainment' describes the case where two or more of the body's oscillatory systems, such as respiration and heart rhythm patterns, become synchronized (Phillips-Silver, Aktipis, & Bryant, 2010). It is the rhythmic responsiveness to self-generated rhythmic signals. A simple block diagram of the process involved is shown in Figure 1 (Phillips-Silver, Aktipis, & Bryant, 2010). In the figure the feedback from the output to the rhythmic input of the entrainment system is the source of the self-entrainment.

It has been considered that complex-bodied humans and animals typically exhibit self-entrainment in their physical activity, that is, a gesture by one part of the body tends to entrain gestures by other parts of the body (Clayton, Sager, & Will, 2004). For example, arm movements in walking could, in principle, be totally independent from leg movements, but in fact they are not. It 'feels' much easier, is more harmonious, and less strenuous if the arms lock into the rhythm of leg movements. A similar effect is reported for the locking of step and inhalation cycles in jogging (Clayton, Sager, & Will, 2004). According to (Bramble & Carrier, 1983) humans need to have synchronization of respiration and body motion during sustained running. They employ several phase-locked patterns (4:1, 3:1, 2:1, 1:1, 5:2, and 3:2), with a 2:1 coupling ratio being most common. In subsequent work, for example, researchers have investigated the coordination between locomotory and respiratory rhythms to assess if entrainment increases the running efficiency (Bernasconi & Kohl 1993) and (McDermott et al., 2003) discovered that running training changes how the locomotor–respiratory coupling system adapts to changing speeds. (Karp, 2007) found that entrainment of breathing to locomotion is a physiological phenomenon in highly-trained distance runners. It is not largely influenced by intensity, and can differ between inspiration and expiration. Thus, the degree and kind of self-entrainment depends on the individual and the task being carried out.

Figure 1. Block Diagram illustrating the process of self-entrainment (adapted from [Phillips-Silver, Aktipis, and Bryant, 2010])



Entrainment and Health

As mentioned above, the concept of Entrainment is readily applicable to the human body and its response to external stimuli. Relevant medical research has considered the behavior of endogenous physiological rhythms in humans (such as the variation of body temperature over the 24-hour cycle), and how the study of those rhythms might be further developed as a tool in the diagnosis of pathological states. The hope is that this could lead to the development of new treatments. Other research investigations consider the field of music therapy, and looking at determining a link between entrainment and socialization. Repetitive rhythms have been found to play significant roles in particular rehabilitative therapies, (Galińska, 2015) and (Thaut, 2015) reviewed how this has led to new neurologic music therapies. Social entrainment is a special case of spatiotemporal coordination where the rhythmic signal originates from another individual (Phillips-Silver, Aktipis, & Bryant, 2010). Social entrainment has two subtypes: mutual social entrainment and collective social entrainment. In the former, rhythmic responsiveness during bidirectional information processing between two individuals results in a `loop' where the output of each individual's rhythmic production provides input for the other's rhythmic processing system. The latter is characterized by a network of input/output connections among individuals in a group. Collective social entrainment may underlie certain forms of collaborative music production and dance, including both structured (e.g., formal performances) and unstructured forms (Phillips-Silver, Aktipis, & Bryant, 2010). The ability to engage in collective entrainment in adult musical activities has been suggested to develop from early music interactions (Phillips-Silver & Keller, 2012). Affective entrainment in social contexts seems to be a predisposition of the infant and mother that helps to regulate the infant's emotional state and guide learning in his pre-verbal environment.

Still, the relationship between entrainment, the stability of biological rhythms, and health is not well understood. There are examples of where relatively stable and entrained biological rhythms are associated with good health. A good example is the enhanced stability of the heart rate afforded by a pacemaker. Conversely asynchrony and instability of rhythmic processes can be associated with pathologies (Clayton, Sager, & Will, 2004). However, entrainment does not necessarily imply stability of biological rhythms, and stability on its own is not necessarily associated with good health. The behavior of brain waves is a case in point: stable brain waves may indicate a condition such as epilepsy, while unstable waves can indicate a healthy state (Glass, 2001). A certain amount of flexibility and dynamic equilibrium is more likely to be associated with health in many systems, as is a degree of "noise", or random variation in normal physiological rhythms (Glass, 2001).

According to (Phillips-Silver, Aktipis, & Bryant, 2010) the capacity to exhibit the simplest form of entrainment emerges when three critical building blocks are in place: (1) the ability to detect rhythmic signals in the environment; (2) the ability to produce rhythmic signals (including rhythmic signals that are byproducts of other functions, such as locomotion or feeding behavior); and (3) the ability to integrate sensory information and motor production that enables adjustment of motor output based on rhythmic input. Observing these three criteria can indicate whether entrainment is being manifested in a healthy or less healthy, or pathological, manner. If the healthy functioning of a system requires a certain degree of entrainment, then either a lack of entrainment, a weakening or even an excessive strengthening of entrainment can be associated with a change to a pathological state (Phillips-Silver, Aktipis, & Bryant, 2010).

Stimulating Kinematic Health through Self-Entrainment

The medical profession are quite aware of the links between music, health and well-being and (MacDonald, Kreutz, & Michell, 2012) considered examples from the various disciplines of music therapy, community music, and music education to illustrate the connectivity. They determined that music has positive effects on health and that its incorporation into particular treatments can bring improvements in current practices. One particular idea is that stimulating an entrainment between auditory rhythmical cues and spontaneous or deliberate movement will boost individual motor performance and lead to enhancements in health and wellness. For healthy people, this means that they should synchronize their movement with the beat of an external music source when dancing or when performing physical and sport activities such as running or cycling. This should lead to measurable improvements in their gait kinematics, for example increased velocity and cadence (Wittwer, Webster, & Hill, 2013), and produce (i) better coupling between breathing and running, (ii) a reduction of energy expenditure, (iii) a general increase in endurance and (iv) a desire to run (Hoffmann, Torregrosa, & Bardy, 2012). Additionally, entrainment has a role in a therapeutic context where movement is constrained by a motor disease (Nombela et al., 2013), (Hove et al., 2012), (Thaut & Abiru, 2010). One study reported on how the concept of entrainment has been integrated into a rehabilitation therapy in patients with movement disorders. The idea is to use external rhythmical cues to help patients' regularize their gait (Thaut, McIntosh, Rice & Prassas, 1993). The patient has to match her/his walking speed to a regular stimulation in the form of a repeated isochronous sound (metronome).

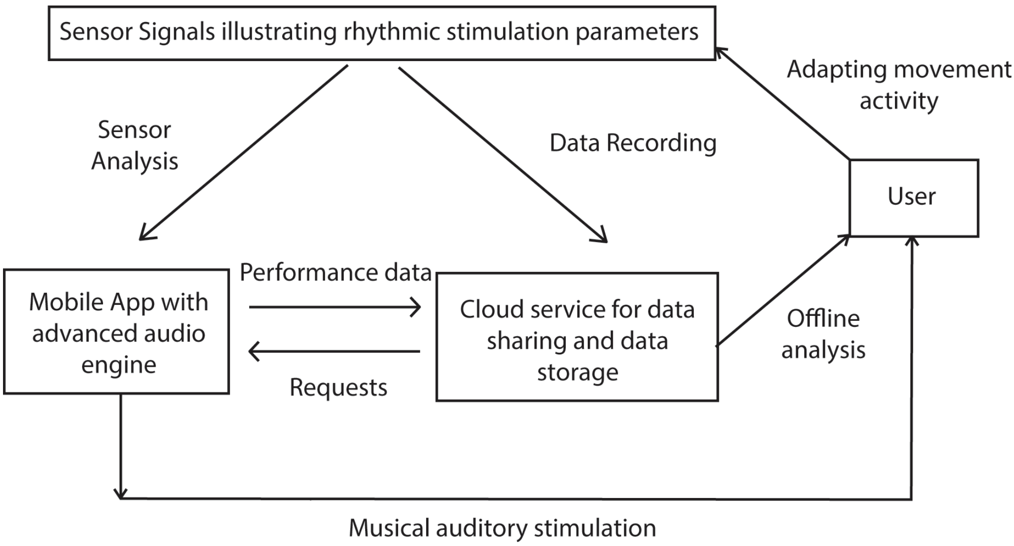
The technology is in its infancy however. There is a lack of sophistication in the means of achieving and maintaining synchronization between the music and user movement. Furthermore, there is a need for more scientific insight into how best to capture and analyze the relevant physiological signals and to relate them to the auditory cues. This was the motivation for the BeatHealth project. Its objective is to realize an intelligent technological architecture that delivers flexible and efficient rhythmical stimulation that can be adapted to any individual's skills via the playlist, whether the individual is healthy or not, which will monitor and enhance features of their movement performance. This leads to next section which will explain the organization of the 'BeatHealth' platform.

ORGANISATION OF THE BEATHEALTH PLATFORM

The fact that there are knowledge gaps in both the current science and technology meant that the BeatHealth project needed to be a highly multidisciplinary endeavor, requiring input from physiology scientists, clinical professionals, music technology researchers, and software engineers. The BeatHealth project was specifically designed for healthy citizens of various ages that engage in physical activity and for Parkinson's disease patients with impaired movement.

Figure 2 illustrates the relationship between the user and the three primary components of the BeatHealth platform. The sensors capture the selected physiological features associated with a user's rhythmic movements. These are analyzed by the mobile phone app which then dynamically adjusts the music tracks on the playlist. As the user perceives the time-varying auditory stimulation they adjust the rhythm of their movement in response, which should eventually result in synchronization. At some point in time, not necessarily when the exercise is being performed, the feature information and performance data from the phone are uploaded to a secure cloud storage service for offline analysis by the user and other permitted parties, such as clinical professionals, trainers, and family.

Figure 2. Interaction between the user and the BeatHealth platform



The novelty of the BeatHealth project means that each component of the platform requires innovation: (i) fundamental research aimed at improving knowledge regarding the parameters that maximize the beneficial effects of rhythmic stimulation on movement kinematics and physiology, (ii) technological development to achieve a state-of-the-art mobile implementation platform with an advanced audio engine that can deliver the rhythmical stimulation that has attributes of portability, flexibility and reliability, (iii) the creation of a new IT service in the form of a network-based application for collecting on the fly kinematic data and sharing them online with the user and others. Portability is a requisite for the mobile platform so that the technology can be used at any time in any place by the user. Additionally, the technology should be flexible in that it should be easy to set up or upgrade as suits the user best wherever they are located. More detail on what is required is described in the following sub-sections.

The purpose of Rhythmic stimulation is the improvement of motor performance. It is a fundamental scientific research component of the project. This aims to improve our knowledge regarding the auditory stimulation parameters that are best suited for entraining movement, and thus enhancing efficiency. This will be investigated for both healthy individuals and patients with motor disorders. For patients with motor disorders it will investigate how to produce more effective novel therapies using such stimulation parameters. It is of particular interest to find rehabilitation strategies that can create long-term benefits that will extend beyond the clinic.

For the audio stimuli, attention is being devoted to understanding which type of stimulus (i.e. existing music or artificially generated signals) best fits the particular individual preferences and functionalities in relation to the motivational effort. Although commercial audio recordings are used now, the platform has the flexibility of allowing the use of artificially generated test signals that can be applied to the scientific study of movement. An example is Amplitude Modulated sounds (Joris, Schreiner, & Rees, 2004). Moreover, if desired, because it is built on Csound (Csound, 2015) the BeatHealth audio engine can be easily reconfigured to run sophisticated computer music derived composition algorithms. There are many avenues to source suitable candidates. A key textbook on algorithmic composition is by (Nierhaus, 2009) and a significant survey paper is *AI Methods in Algorithmic Composition: A Comprehensive Survey* (Fernández & Vico, 2013). Of particular interest might be the algorithmic generation of rhythmic material. An example approach might be a recent stochastic model based application called the *rhythmicator*, which generates high-level rhythms devoid of a specific musical style (Sioros & Guedes, 2011).

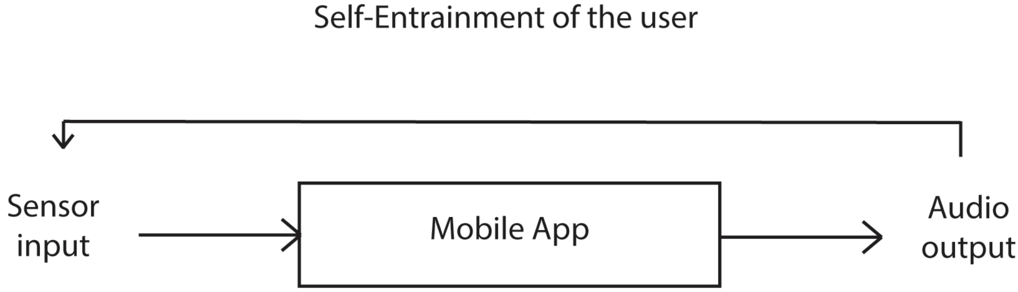
The *Mobile Application* for the BeatHealth system is a redevelopment and extension of the ideas of D-Jogger (Moens, Van Norden, & Leman, 2010), which was previously developed by one group in the project consortium. The structure is that specially-built hardware sensors, equipped with accelerometers and gyroscopes, detect bodily movement and complementary physiological responses are monitored using a heart rate sensor. All this sensor data are transmitted using the Bluetooth standard to a mobile smartphone that is carried by the user that is running a custom-made application. Processing of the sensor signals is required to smooth out noisy fluctuations if the user is engaged in vigorous activity. Special algorithms are required in the case of multiple sensors to fuse the signals together into a single information signal that can then be used to synchronize the auditory stimulation with the rhythm of the activity in an optimal manner. From the information signal a number of features are to be extracted, including accurate estimates of the steps-per-minute, the time of heel strike occurrence, and the step length. The steps-per-minute in particular is important for directing the dynamic tempo adjustment of the audio playback.

The mobile application will contain the playlist of audio stimuli. It will either reside on the device itself or be streamed over the network. The audio engine is built using the Csound platform (Csound, 2015). This has many useful built-in functions including audio playback for a variety of formats and phase vocoder (Sethares, 2007) algorithms for audio time-manipulation. A synchronization algorithm (Moens, Van Norden, & Leman, 2010) that applies the phase vocoder is responsible for the correct alignment of the tempo of the audio stimuli with the movement.

Thus, the user will self-entrain their movements with the audio, which will in turn affect the periodicities of the sensor input. Figure 3 shows a block diagram of the process and it is obvious that it matches the feedback system of Figure 1 and is a skeleton of the larger system shown in Figure 2.

The *Cloud Service* is a network-based application for visualizing and sharing information on the movement performance collected via the application. This will be sent on-the-fly over the internet and made available on a dedicated and secure e-Health platform. The user will be able to create and maintain a profile facilitating ongoing regular assessment and monitoring of physical fitness and wellbeing. The user's health clinical health specialists can also access this information for assessment. Examples of similar current commercial services are Apple's HealthKit (Apple Corp., 2014) and Microsoft's HealthVault (Microsoft Corp., 2014).

Figure 3. The user process of self-entrainment using the mobile app



The current status of the mobile application and the sensor hardware is that much of the development has been completed and it is almost at the stage required to carry out the final proof-of-concept experiments required for the BeatHealth project. The architecture of the Cloud Service has been agreed upon and it will be implemented using a commercial service to ensure data security.

BeatHealth Evaluation

The BeatHealth platform is being validated continuously throughout the project with both healthy users and patients with motor disorders. Close to the end of the project a full evaluation procedure will be carried out. Indicators of change in performance along with changes in health status and the motivation to perform physical activity will be recorded. Alongside this, a full set of beta tests (Brown et al, 2012) to measure the quality of the pre-release software through metrics to assess attributes such as usability and efficiency will be performed. Feedback from user testing will be acted upon before the final release.

RELATIONSHIP OF BEATHEALTH TO UBIQUITOUS MUSIC AND COMPUTING

In its architecture the BeatHealth platform certainly references all the components of Ubiquitous computing given already: It facilitates external sensors for gathering physiological and kinematic information. It runs on a smartphone. Data gathered is stored on a cloud service. Its audio engine is built on the open and flexible computer music programming platform Csound. Lastly, it is context-aware in that it reacts to the user movement by adapting the audio in terms of its beat pattern to the rhythm of the movement of the user. Thus, this respect to the definition of Ubiquitous computing and music, the BeatHealth platform, with some adjustment, could be transformed into an instrument for musical expression or composition. The alignment it creates between movement and music embodies a profound interaction between the human user and the computing system playing the audio: the rhythmic time-scale of the audio adapts to the movement of the user. Thus, the user is engaging physically and mentally with the music in a dynamic feedback system, as in the self-entrainment structure of Figure 1.

This means that the BeatHealth platform can be brought beyond its original intention as an 'exercise app' or a novel therapeutic tool for patients with motor disorders. This can lead to more creative approaches to auralizing all the potential kinematic features derived within the complete BeatHealth framework where specific apps, for example BeatRun (Pollack, 2014), are just particular manifestations of what it can be configured to achieve. Fundamentally, if a mobile device can translate from gesture to music, (Tanaka, 2010) concluded that the distinctiveness of the mobile device creates a form of musical affordance that is propitious to entrainment, and therefore intuitive expressiveness. Thus, facilitating entrainment, as BeatHealth is intended to do, has the potential to create both musically and emotionally satisfying experiences (Labbé & Grandjean, 2014).

The idea of using sensors and mobile technology to make music has been around for over a decade and there are already a number of musical tools that have combined them to make novel instruments. An application called SHAMUS (Essl & Rohs, 2007a) uses striking, shaking, and sweeping gestures to turn a mobile device into a variety of musical instrument including a virtual piano and a rattle. Another is Gliss (von Falkenstein, 2011) which uses a mobile phone accelerometer for real-time music sequence compmosition and playback. A third example is SenSynth (McGee, Ashbrook, & White, 2012) converts data from a combination of sensors that are internal and external to the mobile phone into sound and allows dynamic control of the synthesis parameters along with audio effects. Many more examples can be found in the proceedings of the 'Haptic and Audio Interaction Design' (HAID) (see https://www.interaction-design.org/literature/conference_series/haid) and the 'New Interfaces for Musical Expression' (NIME) conferences (see www.nime.org). A number of papers there deal with the use of sensors such as accelerometers in music making. An excellent review paper on sensors for musical devices is (Medeiros & Wanderley, 2014). It is interesting from a BeatHealth perspective that accelerometers were found to be the most popular sensors used across the many years of the NIME conference (Medeiros & Wanderley, 2014). The customized kinematic physiological sensors of the BeatHealth platform open up new opportunities for such musical applications.

Another pathway for the BeatHealth platform is to extend it to support multiple users: allowing it to deal with user-selectable and/or controllable audio streams or parameters that can be modified by the users' activities. This would lead to it becoming a multi-person compositional or improvisational tool within an environment that promotes kinematic activity. Each setting and activity, for example dance or ensemble music making, could then define various structures for the Beathealth platform. With the real-time modification of multiple-user defined audio information performed as a collective goal, it would transform the activity into a social and artistic experience. As envisioned by (Tanaka, 2010) this interaction should find synchronization on many levels, harnessing the intellectual and the emotional along with the musical and their physical selves. The impact this may have on the sense of wellness could be more profound than just a kinematic motivator alone. Other studies reinforce this conclusion that synchronized interaction is beneficial to the wellbeing of the users. Work in the field on *User Centric Media* (Varni, Mancini, Volpe, & Camurri 2010) examined both Social interaction and Embodied cooperation for multiple users through active listening applications which employed expressive multimodal interfaces to facilitate users interaction. In (Varni, Mancini, & Volpe, 2012) sync4all was introduced for social embodied music listening with real-time gestural sound manipulation captured by sensors embedded in their mobile smartphone, and in (Mancini, Camurri, & Volpe 2013) the Mobile Orchestra Explorer was described as an end-to-end real-time active listening experience of prerecorded music that also supporting authoring and, again, gesture-based playback modification. The evaluation of both applications supported the suitability these applications for creative entertainment and found that the enhanced sense of cooperation gave a very satisfactory experience. Thus, group musical interaction using multiple gesture-driven mobile instruments can bring psychological benefits which, if the BeatHealth platform was adapted to facilitate this, would maintain the BeatHealth philosophy with regard to improving wellness.

The potential of adapting the BeatHealth platform as a multi-user networked music application is challenging. The theory of music making using networked mobile devices and sensors has received some attention over the last decade: a good early work is (Tanaka, 2004) which discussed the collaborative aspect involved in rendering a single music stream from many user contributions. This is a key issue when the mobile phone is an instrument for collaborative use because it necessitates a protocol of interaction for the performance: between the musicians themselves and/or with the audience. This issue of interaction must be elaborated upon as it requires a number of considerations.

To begin with there is the input mechanism. Research examining the suitability of various sensors with mobile technology to facilitate music performance appeared in (Essl & Rohs, 2007b) and (Essl & Rohs, 2010). It was found that visual tracking and touch screens are better for composition systems, whereas analog sensors such as accelerometers or gyroscopes are better for interpretive and improvisational performance (Essl & Rohs, 2007b). This is a useful, practical result, especially for designing a sound-to-gesture interaction strategy with an extended

BeatHealth platform. Other similar work which is even more directly useful to the design of actual musical applications is by (Flores et al., 2010) and (Flores et al., 2014) who examined patterns for musical interaction with computing devices, including mobile devices, within the universe of computer music systems. They found that interaction design patterns, as described in (Borchers, 1999), (Borchers, 2001) and (Tidwell, 2005), are suitable because they facilitate an interdisciplinary design process and work well with design requirements for those technologies specified as ubiquitous computing and mobile devices. (Flores et al., 2010) detailed four user-centered Interaction patterns for musical systems:

1. Natural interaction (i.e. imitate the playing of an acoustic instrument);
2. Event sequencing (i.e. put musical events in a timeline);
3. Process control (i.e. interacting with music process parameters);
4. Mixing (i.e. combining sound layers in real-time).

As it stands the BeatHealth's current audio manipulation technology could be suggested to belong to the interaction pattern of 'Process Control'. Including other interaction patterns to BeatHealth platform would require alterations to its current form. If we adopted the recommendation of (Essl & Rohs, 2007b), then we could consider an application that supports either natural interaction and/or mixing easily in a networked context. A natural interaction pattern among the network members could be broadly similar to a traditional instrumental ensemble except that the instruments would be electronic and gesture-driven. There are precedents to this: the appearance of a community of users of mobile music technology was documented in (Gaye, 2006) and more recently a number of ensembles have formed, such as the Mobile Phone Orchestra or MoPhO (Oh, Herrera, Bryan, Dahl, & Wang, 2010) [1] based in Stanford University USA, the Michigan Mobile Phone Ensemble (http://mopho.eecs.umich.edu), the Helsinki Mo-Pho (http://legacy.spa.aalto.fi/projects/helsinkimopho/) and the Yamaha Mobile Orchestra (Eurotechnology Japan, 2015). A more recent example of ensemble mobile phone music making is a crowdsourcing application: World stage (Wang et al., 2015). This is a pseudoanonymous, location-aware ecosystem designed to connect hundreds of thousands of users in a social-musical game involving expressive musical performance and collaborative musical feedback. They used a 'leaf trombone app' as the instrument (Wang et al., 2015) and thus employed a Natural Interaction pattern. This project also harnessed the power of cloud computing to allow many users to connect and interact together.

A recent thesis has examined the trends in digital socialized music making driven by mobile phones (Bowen, 2013). It recognized that mobile phone ensembles are only at an early stage: managing performer interaction is not insurmountable but extending this to include audience interaction is a significant challenge. Web-based interaction on the phone was considered to be the best option for performances (Bowen, 2013). From a technological perspective its advantages were set out in (Allison, 2012): (1) HTML 5, CSS, and Javascript provide powerful tools for UI creation and can handle accelerometer data and geo-tagging, (2) a technology platform such as Ruby on Rails can easily manage distributed networks of users and accrue all associated benefits, (3) the web offers great flexibility for interface implementation, for example through a shared application, or alternatively a browser, (4) UI code can be highly reusable and should require little modification for different hardware platforms, so more time can be devoted to coding how the system handles received data.

The social interaction scheme of the multi-user network where the musical performers are connected as a network of nodes also requires consideration. (Makelberge, 2012) identified two scenarios for networked music: (1) Collaboration, and (2) Cooperation. Musical artifacts that are the result of highly reciprocal communications among partners that additionally are synchronous and coordinated are considered to be collaborative. Cooperation, in contrast, needs less reciprocity and the work is divided among the partners as individual sub-tasks that are then assembled afterwards. However, examining the original source for these definitions (Dillenbourg, 1999), it is clear that they are not absolute and that there is flexibility. Thus, in a collaborative interaction responsibilities may well be split, but that this division of labour would be horizontal instead of vertical. This implies the responsibilities are highly interwoven and that supervisory roles are not fixed and shift regularly. Collaboration between players producing sound and music can broadly be classified within two general design criteria; capacity and aptitude (Blaine & Fels, 2003). Capacity addresses the number of players the system can accommodate. Aptitude considers the skill of the target demographic as novice or expert players. Up until recently technology-driven collaborative systems were less developed in the field of music composition, possibly because of the barrier that music notation presented to novices (Bligh, Jennings & Tangney, 2005). Recently though, new tools with novel interfaces are overcoming this for novice musicians: unlike an ensemble consisting of musicians who have had to spend years of training in order to control and shape their instrument's feedback into a distinctive voice, the skills required for a collaborative musical experience can be developed within a much shorter period of time (Bengler & Bryan-Kinns, 2013). Descriptions made of these systems include 'open-ended', 'social' and 'democratic', as they are generally intended to reach out to a wide public (Bengler & Bryan-Kinns, 2013). The players' 'sense of control' is an important feature of a collaborative musical experience and influences other important qualities such as the participants' satisfaction with their playing experience, along with their sense of belong to a community (Bengler & Bryan-Kinns, 2013). A sample web-based application is given in (Biasutti, 2015). Participants worked online to collaboratively compose a new piece of music that was achieved by sharing ideas combined with collective decision-making and assessment. They could interact synchronously and solutions were adopted to minimize signal latency. A qualitative assessment showed this to be a positive and stimulating experience. An example of a Cooperative system is by (Miletto et al, 2005), (Miletto et al., 2011a), (Pimenta et al., 2011b). These describe a web-based COoperative Music Prototype DESign (CODES). It is asynchronous as it is unnecessary to handle real-time events (Miletto et al, 2005). A strong emphasis in CODES was on sharing but the coordination of activities happened naturally by whichever member had greater musical ability, or experience, or just was willing to take the lead. An evaluation found it to be successful. The fact that both of these are web-based implementations should render them easily transferrable to any mobile platform.

Following on from this, synchronization techniques are required for preserving the coherence of rhythmic timing (Nyomen, Chandra, Glette & Torrssen, 2014) in collaborative music systems. The performing entities can be interpreted as a group of oscillators and should use mutual feedback to align themselves at a common frequency and phase. Synchronization mechanisms can be either centralized or decentralized (Bojic & Nymoen, 2015). A centralized synchronization mechanism means that there is one entity or a limited number of entities responsible for time synchronization. If there is only one entity, then this mechanism is susceptible to a single point of failure problem. Otherwise, if there is more than one entity, then these entities must be organized hierarchically (Bojic & Nymoen, 2015). It is time consuming to achieve a hierarchical structure and it is also hard to maintain the structure as entities join and leave the system. In contrast, the decentralized mechanism has the advantage of being easily scalable. Mathematical models of the process for self-organization to achieve synchronization are available (Pikovsky, Rosenblum & Kurths, 2001). Two well-known models are the Phase-coupled and Pulse-coupled oscillator models (Bojic & Nymoen, 2015). The phase coupled oscillator model is known to be computationally demanding as it is necessary to calculate values for all oscillator phases throughout the synchronization process. With Pulse-coupled oscillators excessively strong coupling can lead to a cessation of rhythmicity (Mirollo and Strogatz, 1990). Synchronous systems have been implemented in the computer music literature. (Lambert, 2012) introduced a 'Stigmergic' model for oscillator synchronization to build an interactive multi-user musical application. Another work by (Nyomen, Chandra, Glette & Torrssen, 2014) used a model of pulse-coupled oscillators, inspired by (Mirollo & Strogatz, 1990), to resolve initial tempo differences between nodes in a collaborative music performance system so that they converge to a common musical beat (Nyomen, Chandra & Torrssen, 2013). However, there is still insufficient experience in the computer music literature to fully inform the choice of synchronization technique. Thus, each interaction scenario must have its own solution derived.

There are a number of other issues that must be taken into account when configuring multi-user collaborative networks for music. One is interface design, and (Blaine & Fels, 2003) identified the most significant context elements along with other constraints necessary for a musical medium. Another is network topology. Currently, most arrangements adopt a peer-to-peer communication model (Alexandraki & Akoumianakis, 2010) although this can have latency problems, which can be very disruptive to real-time collaborative processes. The alternative is to employ a streaming server as an intermediate node in a star topology that can provide increased outbound network bandwidth compared to the outbound bandwidth of each of the connected clients (Alexandraki & Akoumianakis, 2010). A tool for evaluating configurations of collaborative performance systems for digital music across six dimensions was proposed in (Hattwick & Wanderley, 2012) and could be useful within the design process.

This section has explained a number of aspects of mobile-based music systems and in particular multi-user collaborative schemes. Careful consideration is required to extend the BeatHealth platform for these systems, particularly with regard to interaction. The Case Studies in the next section will offer some example-oriented explorations to illustrate how an adapted BeatHealth platform could actually be configured for ubiquitous music applications.

CASE STUDIES

Case Study No. 1

To outline the first Case study for a Ubiquitous networked BeatHealth musical application it is proposed that it should be web-based and involve multiple-users interacting in a collaborative manner. It seems to be most straightforward to apply the BeatHealth platform with a 'Mixing' or 'Process Control' pattern. Employing either of these two patterns audio information that contains musically coherent material, in the form of multiple streams, could be pre-loaded onto the mobile devices or be received from an external service or source. The ensemble of users would all wear BeatHealth sensors, and work together with the BeatHealth application to manipulate the audio synchronously in real-time. A decentralized synchronization model for an ensemble of independent users could extend the entrainment enabled by BeatHealth to a collaborative ensemble. An example of such an application is the MobileDJ (Lo et al, 2013). Here, a portable music player provides audio tracks and the processing is divided into two functions: musical effect control and audio time-based control. The input comes from a lightweight armband equipped with sensors, which is manipulated by a specially made glove. To support the social interaction between users, MobileDJ includes a location-based, user discovery function, which allows users to discover other "unconnected" players nearby. Users that are connected share music and have the power to modify it together. Aside from requiring a specific armband controller the BeatHealth platform could be adapted to create an application that is similar in spirit. The BeatHealth sensors would detect kinetic gestures from the users and a musical application would interpret them to trigger particular audio processing effect algorithms in a beat-aligned manner. These effects could be extensive, going far beyond the current time-based effect BeatHealth possesses currently. Other sources of inspiration for the presentation of the musical material to the users could be from sync4all (Varni, Mancini, & Volpe, 2012) or the Mobile Orchestra Explorer (Mancini, Camurri, & Volpe 2013). One aspect not formally treated in any of the three papers discussed here is that of synchronization. The BeatHealth platform is in a stronger position to rectify this gap, and if the number of users is does not exceed the computational resources available, a phase-coupled synchronization model could be employed.

Case Study No. 2

Moving to a second Case study, the BeatHealth system could be easily adapted to a music application with distinctive rhythmic material that could be adapted on the fly by users moving in time together. BeatHealth is specifically designed for maintaining entrainment and synchronization. This suggests an Event Sequencing pattern where the audio material could be melodic or purely rhythmic. Mobile phone applications that could provide some inspiration are (Lantz & Murray-Smith, 2004) and (Erkurt, Jylhä & Rocchesso, 2010). (Lantz & Murray-Smith, 2004) developed a rhythm interaction algorithm for a mobile platform that utilized an accelerometer sensor. (Erkurt, Jylhä & Rocchesso, 2010) created a tutor application in which the interaction is user clapping and the idea is to negotiate mutual coordination with a virtual crowd that is also clapping. The clapping starts asynchronously but if the user claps to a steady rhythm then the user can entrain to the virtual crowd. Feedback is multisensory. The user can set targets to allow them to improve their skills such as maintaining a consistent tempo. BeatHealth could be developed into an educational application where significant user movement is required, as might occur with dance, either in a game scenario or for training. The rhythmic pattern could be simple or complex, and could also evolve dynamically requiring keen user concentration so as not to lose alignment. The inclusion of networking between users would require finding a suitable synchronization model, which could be a challenge technically, but the collective experience of the music- or rhythm-making should be very socially rewarding.

Case Study No. 3

A final Case study would be to rise to the challenge of creating a networked BeatHealth musical instrument ensemble that uses a Natural Pattern of interaction. (Won Lee and Freeman, 2013) is a helpful reference. In this work audience members participate as individual musicians and generate sound from their seats using mobile phones as musical instruments. A 'Master' musician is required to control the high-level musical structure (i.e. the chord progression) but does not create any sound themselves. This implies a cooperative scenario (Makelberge, 2012) with a centralized synchronization strategy (Bojic & Nymoen, 2015). The 'Master' determines the harmonic content (scale) of the instrument. The audience plays the instrument note by note and generates sounds in a harmonically controlled manner. The audience's instrument is a simplified eight-key instrument with the pitches of the eight based on the current chord to maintain consonance and prevents the music from sounding uncontrolled. Manipulations permitted are duration, polyphony and amplitude modulation. No rhythmic guidelines are given. To keep audience participation going a pattern-broadcasting function was implemented (Won Lee and Freeman, 2013). Those who follow a pattern have the pleasure of making music in synchronization with others. BeatHealth could be modified to extend the capabilities of this system. Its sensor inputs could be used to map to and facilitate a greater range of audio effects but also to improve the rhythmic and melodic synchronization between users. All users will be inexperienced with the instrument interface and the potential for entering melody notes in a rhythmically incorrect manner will be high. The BeatHealth sensors could be set up to monitor users' body movements, such as foot-tapping, that can then be used to align the set of melodic lines back into rhythmic coherence. Smaller adjustments to get it 'just right' could be triggered by other sensors. The 'Master' musician acting as a conductor then can exert other influences over the dynamic musical structure through various gestural expressions to build musical tensions, synchronizing the audiences' musical patterns to their master tempo, and therefore enhancing the overall performance. The whole experience would be immersive and very satisfying from a group perspective as it requires the ensemble to be concentrated together in music and movement.

These three Case studies offer some possibilities for the BeatHealth platform. Other ideas could come from work such as (Ciufo, 2003) which examines design concepts and control strategies for interactive improvisational performance, which could also be useful for integrating BeatHealth even more deeply with audience-oriented music making. Strategies for Whole Body Interactive performance systems are discussed in (Lympouridis, 2012) and are also important as they can help the designer to think more about the type and physicality of the musical interactions using an extended BeatHealth platform with a larger complement of sensors than it employs currently.

CONCLUSION

This work has introduced and then discussed the scientific background to the BeatHealth project. The features of the BeatHealth platform were shown to correlate well with the definitions of Ubiquitous computing and music systems. This was followed with an analysis looking at how it can be brought beyond its original health and therapeutic context to fit into the world of computer music. The main idea was that it can be adapted to facilitate musical interaction among multiple users using sensor-monitored gestural inputs. The intention is that beat-synchronized applications derived from this will deliver an enhanced sense of participation, and arising from this a sense of wellness, to collectives of users. A number of technical challenges have been discussed, particularly in relation to interaction for music computing applications. This included detail on the issues of interaction patterns, cooperation versus collaboration, and synchronization. This was followed by three Case Studies that considered different musical interaction patterns applied to the BeatHealth platform to create multi-user systems that could be used for music creation and processing. References were made to previous works to show how the BeatHealth platform fitted in with these applications and to show how it might augment them. The overall conclusion is that the BeatHealth platform can be tailored such that it can find a place in the domain of Ubiquitous Computing and Music. With just some imagination and the requisite software development it can easily be used to realize advanced interactive musical performance tools that are accessible for professional computer musicians and amateurs alike.

As a final note, there is optimism regarding the future of these types of mobile phone-led interactive musical technologies. Papers are being published regularly in the field, for example (Barraclough et al., 2015). (Bowen, 2013) thinks that it is by mobile phones that computing itself will become even more ubiquitous and that it is certain to continue to grow as the phone itself will become even more advanced. Additionally there are plenty of incentives for instrument builders to improve the music-making experience with mobile phones: the ease of implementation, the facilities for dissemination and the potential markets all form an attractive outlook for them. An extended ubiquitous BeatHealth platform should be a tool that can easily become a part of this future.

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ENDNOTES

1. Note that the Apple iPhone was the platform of choice here (the same as for the MoPhO). The BeatHealth platform works on Android only and will not be ported to iOS. Although iOS currently has performance advantages over Android in terms of audio processing, this will change as the Android operating system is constantly improving (Lobao, 2015).

Joe Timoney completed his PhD in Electronic Engineering at TCD, Ireland in 1998. He joined the Dept. of Computer Science at Maynooth University in the following year. He teaches on undergraduate programs in Computer Science and in Music Technology. His research interests are based in the area of audio signal processing, with a focus on musical sound synthesis and the digital modelling of analogue subtractive synthesizers. He is also a DIY electronics enthusiast and has participated in a number of national Maker Fairs as part of the Maynooth University club. He is a member of the Audio Engineering Society.

Sean O' Leary has been working on the BeatHeath project since Spring, 2015. Prior to this he was a postdoctoral researcher at IRCAM in Paris, France and Orange Labs, Lannion, France.

Dawid Czesak is a Software Engineer at NUI Maynooth, currently working on mobile application design and implementation.

Victor Lazzarini is a Senior Lecturer at Maynooth University in Ireland. He is a graduate of the Universidade Estadual de Campinas (UNICAMP) in Brazil, where he was awarded a BMus in Composition. He completed his doctorate at the University of Nottingham, UK. His interests include musical signal processing and sound synthesis; computer music languages; electroacoustic and instrumental composition. He co-edited "The Audio Programming Book" (with R. Boulanger, Cambridge, Mass, MIT Press, 2010), and has published extensively in the above areas.

Eoghan Conway is a Software Engineer by trade. He holds a BSc (hons) in Computer Systems from the University of Limerick (2003). Eoghan has worked on a variety of projects funded by Enterprise Ireland and the European Union involving all aspects of software engineering, web application design and mobile application design.

Tomas Ward is Senior Lecturer in Electronic Engineering at Maynooth University (since 1999) where he leads the Biomedical Engineering Research Group. Dr. Ward holds B.E. (Electronic Engineering), M.Eng.Sc. (Rehabilitation Engineering) and Ph.D (Biomedical Engineering) degrees from University College, Dublin. His academic research includes the application of neurotechnology for neurorehabilitation particularly in stroke and signal processing for connected health. Dr Ward serves on the Engineering Sciences committee of the Royal Irish Academy and previously on the Irish Research Council He is a Senior Member of the IEEE since 2011. Dr Ward has authored more than 200 peer-reviewed publications and has supervised to completion 20 research students (12 PhD). He has licensed a range of technologies to industry since 2009 including sensor streaming technologies for e-health, over the air programming and mobile health applications. In 2014 Dr Ward took a role as VP of Engineering (and later COO) at Syntrogi Inc - a San Diego neurotechnology company developing brain state decoding middleware for neural interfacing applications.

Rudi Villing holds a B.Eng in Electronic Engineering from Dublin City University (1992) and a PhD from Maynooth University (2010) in which he studied and proposed new methodologies for sensorimotor investigation of pscyho-perceptual phenomena in auditory processing. Previously, he worked extensively with industry as product architect with Euristix Ltd. and Marconi plc. creating the architecture for strategic network management technologies before taking a lecturing position with the Electronic Engineering department in Maynooth University in 2002. His key skills are system integration, sensor signal processing, and communications. Dr Villing has a special interest in physiological and perceptual inspired signal processing for connected health. He is currently leading the sensor integration activities in BeatHealth, a collaborative project (STREP) co-funded by the European Union under the Seventh Framework Programme (FP7).