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APPROPRIATING BIOSENSORS AS EMBODIED CONTROL STRUCTURES IN INTERACTIVE MUSIC SYSTEMS

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Abstract: *We present a scoping review of biosensors appropriation as control structures in interactive music systems (IMSs). Technical and artistic dimensions promoted by transdisciplinary approaches, ranging from biomedicine to musical performance and interaction design fields, support a taxonomy for biosensor-driven IMSs. A broad catalog of 70 biosensor-driven IMSs, ranging in publication dates from 1965 to 2019, was compiled and categorized according to the proposed taxonomy. From the catalog data, we extrapolated representative historical trends, notably to critically verify our working hypothesis that biosensing technologies are expanding the array of control structures within IMSs. Observed data show that our hypothesis is consistent with the historical evolution of the biosensor-driven IMSs. From our findings, we advance future challenges for novel means of control across humans and machines that should ultimately transform the agents involved in interactive music creation to form new corporalities in extended performative settings.*

Keywords: *biosensors, appropriation, interactive music systems, control structures.*

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INTRODUCTION

The advent of novel, portable, and more accessible microcomputers in the 1970s hailed a cultural transformation in contemporary music practices, in particular, improvisatory musical practices. This transformation led to a new aesthetics of musical performance called “interactive composing” (Chadabe, 1984). Interactive composing implies the use of electronic instruments that make musical decisions in response to the human performer sharing control of the musical process, thereby establishing a new critical space to explore communication between the human(s) and machine(s). Interaction is a concept frequently adopted across multiple musical expressions and activities, such as musical performing, composing, or listening. Despite the common use of the word *interactive* in musical practice, interactive music denotes a particular compositional approach that emerges from a feedback loop between humans and computational agents (Rowe, 1992). Figure 1 shows a prototypical architecture of an interactive musical system (IMS) that involves two agents: a human and a computer. Yet, IMSs can adopt somewhat fluid multiagent architectures when incorporating multiple computational or human agents, in line with the practice of ensemble practice in instrumental music. As an example, the interaction between a human and a computational agent or between computational agents and an audience (i.e., multiple human agents) is a typical multiagent IMS approach (Levin, 2006). Even an IMS featuring computational-only agents has been pursued (Codognet & Pasquet, 2009).

The interplay and communication flux among agents in an IMS is bidirectional, using varying degrees of control and feedback instantiated by their sensor and actuator components, respectively. Furthermore, the natural and artificial cognition and memory at the core of each agent recognize and process all the sensed data and then act accordingly.

Although acoustic instruments offer several degrees of interpretational affordances, digital instruments (such as IMSs), with their score-driven instructions written for the metamachine (nonphysical) nature of electronic and digital musical systems, allow for an augmented degree of arbitrary relations between the control and feedback (Magnusson, 2009). IMS practices that rely on metacompositional practices range from random or stochastic procedures to rule-based (Chadabe, 1997) and cognitive models (Çamcı, 2012).

Agents in an IMS can influence, affect, and alter the underlying compositional structure, and the musical work emerges through this control and feedback process (Drummond, 2009). Particular emphasis is given to the sensing and control structures of an IMS as well as the IMS’ potential for agency. Furthermore, the design of frameworks in IMSs are increasingly fostering interdisciplinary

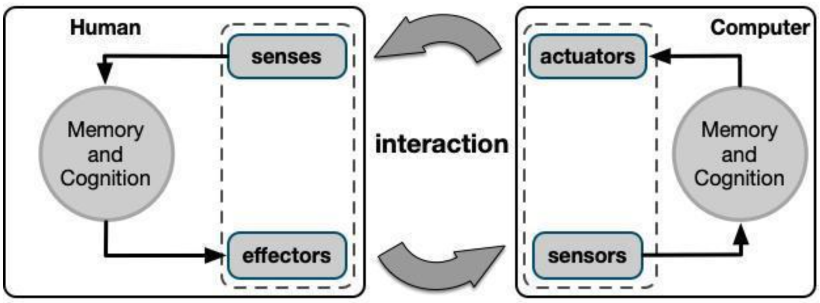

Figure 1. An interactive system architecture as a control and feedback loop, adapted from Bongers (2000).

dialogues, such as human–computer interaction (HCI) and music focusing on the intersection among an IMS, a human body, and the biosensing technologies. These new design strategies have expanded IMSs toward environmental sensings, such as the exploration of video-based tracking as a control structure for interactive music creation (Caramiaux & Tanaka, 2013; Jordà, Geiger, Alonso, & Kaltenbrunner, 2007) and biosensing technology (Arslan et al., 2005).

Biosensing employs biosensors—analytical devices that convert a biological and chemical event into a measurable signal—to provide opportunities for sensorimotor control, thereby affording musicians performing with an IMS various experiences with their bodies. Coupling body physiology and music promotes new interaction modes and, ultimately, impacts music by re-envisioning the role of the musician's body during the performance (Tanaka, 2019). Furthermore, compelling creativity questions arise for both researchers and IMS musicians when the use of biosensors is expanded to capture the audience's physiology. For example, by capturing high-level cognitive traits from audience members using biosensors, interactive musicians can ultimately access the audience's emotional states during an ongoing performance, thus unpacking new strategies for interaction across multiple humans and computational systems.

More recently, IMS musicians appropriated biosensors as expressive control structures for controlling the generation of music in IMSs. In this context, *appropriation* refers to a recontextualization of specific technology beyond its primary application (Naccarato & MacCallum, 2017). Throughout our study, we verify that biosensing allows the scope of interactions available to the musicians to expand. Biosensors in close contact with the body promote the capture of a wide range of movements—from low-to-high body expressions—typically inaccessible through traditional sensor tracking devices, such as video tracking. By lower- and microexpression levels, we mean both the smallest controllable and perceivable human motion—such as small facial expressions—and the continuous motion of various parts of the human body, such as the rhythmic patterns of breathing or pulse. Therefore, as a control structure for musical interaction, biosensing decodes inner structures of the performer's body as a control variable in an IMS.

Additionally, biosensing captures a particular type of interaction when it measures unseen electrical activity captured through sensors placed on the surface of the skin. For example, electromyography measures muscle activity, electroencephalography estimates brain activity, and electrocardiography measures heart activity. IMS musicians adopt biosensing as a control structure for driving IMSs with high degrees of expressiveness (Caramiaux, Donnarumma, & Tanaka, 2015; Donnarumma, 2011; Erdem, Schia, & Jensenius, 2019). Body movements and their rich and complex gesticulation is increasingly explored in HCI by using touch screens, depth cameras (e.g., Kinect camera), video controllers, or smartphone motion sensors.

Fostered by artistic and technological developments, namely open-source biosensing devices, biosignals have received increasing attention in recent years as control structures in interactive systems and HCI. To advance the understanding, categorization, and classification of these biosensing IMSs, researchers have proposed various taxonomies (e.g., Christopher, Kapur, Carnegie, & Grimshaw, 2014; Da Silva, 2017; Drummond 2009; Ortiz, Grierson, & Tanaka, 2015; Prpa & Pasquier, 2019). Christopher et al. (2014) debated the impact of new emerging paradigms incorporating brain activity through electroencephalographic signals (EEG) in music making. Drummond (2009) focused on the potential interactions with IMS. Da Silva (2017) presented a taxonomy characterizing biosignal data sources that balanced expectations around their use in HCI. It highlighted aspects such as controllability and acceptability, which are fundamental to the design of biosensing systems in real-world cases such as medical monitoring in Fitbit applications. Ortiz et al.'s (2015) taxonomy concentrated on, in particular, EEG-based musical practice. Finally, Prpa & Pasquier (2019) provided a comprehensive catalog of 40 works guided by a taxonomy to categorize brain-computer interfaces (BCI) in contemporary artworks that incorporate EEG signals mapped to music, video, painting, print, and virtual environments. However, none of these studies considered the interplay between the biosignals from an HCI perspective and the potential interaction within a musical system. We believe our proposed taxonomy can fill that gap in the literature.

By integrating both functional and empirical categories in our proposed taxonomy, we provide a more detailed description of an IMS and help envision future pathways for biosensing IMSs. For example, the recent growth in the use of nonobtrusive devices (i.e., the miniaturization of devices) for capturing biosignals promotes multiple performers' potential interactions in an IMS due to more pervasive and easy-to-use devices. Another example of the interplay among functional and empirical categories is the correlation between the musician's perceived controllability over the system and its response type in terms of musical structures. A highly controllable signal fosters manipulation of higher musical structures, such as differences in volume or frequency.

The present study presents an integrated taxonomy for analyzing biosensor-driven IMSs. Focusing on functional and empirical dimensions, our taxonomy encompasses a broad catalog of IMSs, spanning a time frame from 1965 to 2019. Additionally, we sought to identify any visible trends across IMS biosensing controls, responses, and affordances, while noting the abstraction levels that have been considered in IMSs from raw biosignal. Our study raises the hypothesis that biosensing technology in IMSs is expanding the array of control structures within IMSs and can be seen as a new mode of control among human and musical systems—opening new creative avenues for interaction, expressivity, and embodiment in music performance (see also Tanaka, 2019).

The remainder of the paper is organized as follows. The Methods section details the research methodology for data collection and analysis. Then the Biosensing Technologies: A Technical Overview section presents biosensing technology according to its typology and specifications. The A Taxonomy for the Analysis of Biosensing in IMS section characterizes the multidimensional taxonomy adopted in our study, both the functional and empirical categorizations. The section Biosensing in IMS: A Temporal Perspective revises temporal applications of biosensing technologies within biosensor-driven IMSs presented in the catalog, based on visible trends and extrapolated from global statistics applied in the catalog's items across IMS biosensing control, response, and affordances. In the section Toward an Embodied Control Structure in IMS: Future Challenges, we outline novel perspectives on the integration of biosensing when designing new musical interfaces. The paper closes with the Conclusions and Implications sections, in which we discuss the novelty, originality, and the limitations of our study. Our aim is to discuss the future challenges involved in embodied control in IMS creations through the use of biosensors.

METHODS

In pursuing the main objective of our study—that is, an integrated taxonomy for analyzing the functional and empirical categories of biosensor-driven IMSs—we also aimed to identify historical trends in IMSs regarding (a) biosensor adoption as control structures, (b) response types in terms of the musical output of the system, and (c) performative affordances. The process of identifying these trends would allow us to classify IMSs according to their appropriation of existing biosensor technology. Moreover, such a process also would raise our awareness of the human body in performative musical contexts, which ultimately could lead to identifying artistic and technical challenges in a future roadmap for the biosensor-driven IMSs. To this end, the following four-fold methodological goals were adopted: (a) compiling a comprehensive catalog of biosensor-driven IMSs, (b) defining a biosensor-driven taxonomy of IMSs, (c) applying the proposed taxonomy to the catalog, and (d) identifying historical trends from the resulting taxonomy application data.

To compile the comprehensive catalog of biosensor-driven IMSs, we adopted a scoping-review method, a process particularly suitable for a wide range of transdisciplinary fields (Arksey & O'Malley, 2005). The search for biosensor-driven IMSs was conducted online on relevant scientific archives, such as IEEE Xplore, ACM Digital Library, Google Scholar, as well as art catalogs and musicians' websites. We completed the entire online search during April 2020. To filter the search, we mapped key concepts to their related sources: *biosensors, interactive music systems, music, sound, HCI, performance, embodiment*, and *biophysical*. We manually surveyed the retrieved documents to identify their potential to be included in our catalog from the collected sources. To this end, we took into the catalog only entries that met the following two criteria: (a) biosignals from either performers or audience members were present, and (b) biosignals were mapped to sonic feedback and response. The first criterion ensured the inclusion of biosensor-driven works, while the second criterion specified the underlying qualities of an IMS.

Furthermore, we reviewed each source document that met the above criteria for related sources. For example, in scientific literature, we inspected the reference section to identify additional potential biosensor-driven IMSs that met our criteria. A particularly relevant case was that of Prpa and Pasquier (2019), who had compiled a list of 40 interactive BCI artworks.

To define a biosensor-driven IMSs taxonomy, our point of departure lays within three earlier taxonomy proposals by Prpa & Pasquier (2019), Drummond (2009), and Da Silva (2017), which focused on artistic categorization, sonic feedback, and HCI, respectively. The lack of an articulated taxonomy reflecting the interrelationships of both functional and empirical categories has significant impact when defining mapping strategies among musical events and functional properties of a biosignal, such as perceived controllability. To accommodate both these categories, we compiled all dimensions featured in each previous taxonomy and empirically tested them in our catalog by annotating each entry according to the complete set of dimensions. We then pursued simplifying the adopted dimensions to reduce redundant information and organized them uniformly according to our functional and empirical categories. Due to the subjective nature of most IMSs and with the goal of unifying the proposal, we redefined some dimensions to account for relative description spaces rather than specific discrete types. In the final step, we gave careful consideration to the adoption of continuous or discrete spaces in each dimension within the taxonomy. The decision between the adoption of continuous or discrete spaces in each taxonomy dimension was done by inspecting their manifestation on the collected catalog data and by surveying existing literature on the topic. Once the taxonomy was finalized, we adopted it to categorize and compare all entries of the biosensor-driven IMS catalog.

Regarding the process of identifying the historical trends resulting from the taxonomy, we plotted the data of each dimension of the taxonomy to reflect its temporal evolution with multiple resolutions. We aimed at finding points in time where abrupt changes in the defined dimension occurred. Peaks and valleys in the data exposed various appropriation strategies of biosensors in the scope of IMSs. Peaks indicate historical moments where the appropriation of biosensors in the artistic IMS practice had greater attention by musicians. Conversely, valleys denote historical moments where the appropriation of biosensors had a steep decline.

The ultimate goal of the taxonomy was to articulate the functional and empirical dimensions of IMSs. A preliminary data analysis identified where explicit representative dimensions were noticeable. Thus, we focused on the analysis and interpretation of the following dimensions: type of biosignal used, the type of response expected from a specific IMS, and the performative affordances IMS musicians seek when conceiving an IMS. Conformity in terms of these temporal marks across dimensions were the basis for extrapolating representative periods of the biosensor-driven IMS practice as well as for extrapolating current directions, challenges, and future endeavors in this line of research and artistic practice.

BIOSENSING TECHNOLOGIES: A TECHNICAL OVERVIEW

Human psycho-physiological activity has multiple bodily manifestations, including biophysical, biochemical, bioelectrical, and biomechanical processes, which we define collectively as biosignals, in line with Northrop (2017) and Saltzman (2015). Recent sensor technology has been developed to detect and measure these manifestations, notably to support medical care (Cacioppo, Tassinary, & Berntson 2007; Webster & Eren, 2017). Although some biosignals can be measured only under controlled conditions (e.g., magnetic resonance imaging), others can be obtained unobtrusively using inexpensive sensor devices. Examples include motion, respiration, brain activity, skeletal muscle activity, cardiac rhythm, and skin functions, to name a few. Beyond their medical applications, biomedical sensing technologies have been attracting the attention of interactive musicians, who are increasingly adopting this technology to control the parameters of interactive digital systems.

Over the past few decades, researchers have proposed a wide range of taxonomic perspectives of biosensing, rooted in various disciplines and applications. Horowitz and Hill (1989) organized sensor technologies according to their circuit design, while Sinclair (2000) arranged them according to the physical quantity measured by a sensor (i.e., the type of energy: radiant, mechanical, gravitational, electrical, thermal, and magnetic). Bongers (2000) categorized sensors based on the ways human movement changes the surrounding environment. In the context of IMSs, the most common control structures relate primarily to bioelectrical or biomechanical processes, resulting in, for instance, motion, airflow, or muscle activity. We grouped the sensors by their specific functions and, in Table 1, we provide a list of common sensors, their abbreviations, and functions. All the abbreviations adopted in our study stem from Heck (2004).

Table 1. Biosensing Technologies: A Comprehensive List of Bioelectric and Biomechanical Sensors Grouped According to Their Specific Function.

Bioelectric sensors		
ECG	electrocardiogram	measures the electrical activity of the heart using electrodes placed in contact with the body surface (Malmivuo & Plonsey, 1995; Votava & Berger, 2011)
EDA	electrodermal activity	Measures, through electrodes applied to palms of the hands or soles of the feet, the skin conductance changes that result from the sympathetic nervous system activity (Boucsein, 2012; Ortiz, Coghlan, & Knapp, 2012)
EEG	electroencephalogram	measures the electrical activity of the brain using electrodes in contact with the scalp (Malmivuo & Plonsey, 1995; Ortiz et al., 2015)
EGG	electrogastrogram	measures the electrical signals associated with the gastric muscles via electrodes in contact with the stomach region of the skin (Chen, Xu, Wang, & Chen, 2005; Yin & Chen, 2013)
EMG	electromyogram	measures the electrical activity of surface (sEMG) or internal (iEMG) muscles using electrodes attached noninvasively to the body surface (in the sEMG) or, for the iEMG, placed invasively in contact with the muscle fibers (Basmajian & Luca, 1985; Nagashima, 2002)
EOG	electrooculogram	measures the corneal-retinal potential variation associated with the eye movement (Kopiez & Galley, 2002; Ramkumar, Kumar, Rajkuma, Ilayaraja, & Shankar, 2018)
TEMP	temperature	measures body internal temperature via thermistors, thermopiles, infrared, thermal imaging, or analogous elements
Movement sensors		
ACC	accelerometer	measures static (i.e., relative to gravity) or dynamic acceleration (e.g., due to motion, shock, or vibration) generally employing a damped mass mounted on a spring (Donnarumma, Caramiaux, & Tanaka, 2013; Niu et al., 2018)
AF	air flow	measures the air inflows and outflows typically by way of a thermal element or a spirometer turbine (e.g., can enable air volume estimation) placed in the nostril or mouth (Hedrich, Kliche, Storz, Ashauer, & Zengerle, 2010).
FSR	force sensing resistor	measures the load applied in tension, compression, or torsion typical via a force-sense resistor (FSR) or strain gauge (Lee et al., 2018; Schwizer, Mayer, & Brand, 2005).
FLEX	flex sensors	measures the amount of flexion in an element applied to the body surface by way of a bend sensitive resistor, strain gauge, or optical fibers (Saggio & Orengo, 2018; Torre, 2013)
GYR	gyroscope	measures angular rate through a vibrating structure or spinning disc (Höfer, Hadjakos, & Mühlhäuser, 2009; Passaro, Cuccovillo, Vaiani, Carlo, & Campenella, 2017)
MAG	magnetometer	measures the strength of a magnetic field (e.g., of the earth) or magnetic anomalies in a particular location (Essl & Rohs, 2009; Merayo, 2002)

(continued)

Table 1. Biosensing Technologies: A Comprehensive List of Bioelectric and Biomechanical Sensors Grouped According to Their Specific Function. (Continued)

MMG	mechanomyography	measures via ACC, FSR, piezoelectric, or strain gauge sensors the skin displacement as a result of muscle activation (Donnarumma et al., 2013; Talib, Sundaraj, Lam, Ali, & Hussain, 2019)
PST	position sensors	measures the angular and tilt position of the body typically through linear or rotary adjustable resistors that change their electrical properties with the position of a wiper element (i.e., a moving contact for making connections with the terminals of an electrical device; Y. Park, Lee, & Bae, 2014)
RESP	respiration sensors	measures the displacement of the chest induced by the inhaling and exhaling activity using a piezoelectric element, a pressurized tube, or inductance variations in a coil embedded in fabric (Vidyarthi, Riecke, & Gromala, 2012).
Optic Sensors		
MOCAP	motion capture/tracking	measures the motion of an individual with varying degrees of sensitivity via multiple video cameras (visible or infrared, with optional depth-sensing), passive infrared sensors, ultrasound, or related sensors (Bevilacqua, Naugle, & Valverde, 2001; van der Kruk & Reijne, 2018)
PPG	photoplethysmography	Measures, via sensors using an illumination element in the visible or infrared range and a photodetector, the blood volume changes as expressed by the amount of reflected or transmitted light that changes with the perfusion variations associated with the blood pumping activity of the heart (Alian & Shelley, 2014)
Environmental Sensors		
AP	air pressure	measures via a force collector (e.g., a diaphragm) the tension resulting from the force applied by a gas (e.g., blowing through a mouthpiece) or liquid over a known area (Nagashima, 2002)
HUM	humidity sensors	measures the volumetric water content of a medium typically through a resistance or capacitance variation sensor
LUX	luminosity	measures the intensity of light (visible or invisible) that reaches a photosensitive element

In this section, we presented the most-used biosensor technologies per functional categories. In the next section, we provide a description that takes into consideration the nature, specificities, and peculiarities of the type of signal biosensors capture. By classifying the signal sources as a basis for the taxonomy of biosensor-driven IMSs, we propose an analysis of IMSs both functionally and empirically.

A TAXONOMY FOR THE ANALYSIS OF BIOSENSING IN IMSs

In this section, we propose a taxonomy to classify biosensor-driven IMSs. We apply our taxonomy to the collection of 70 IMSs that we present in a table below. The inclusion of IMSs in the catalog followed the criteria stated in Methods.

Figure 2 shows the taxonomy categories featuring a twofold (functional and empirical) organization. The functional category is adapted from an existing taxonomy (Da Silva, 2017). We subdivided the functional category into dimensions to detail biosignals from HCI and signal-processing perspectives according to perceived user controllability, device obtrusiveness, feature observability, and signal property. The perceived user controllability and device obtrusiveness dimensions consider the perceived accuracy of user control over the degrees of freedom of a biosignal and the ergonomic implications of the biosensors. Feature observability and signal property dimensions describe time and frequency-domain signal attributes, such as the description of typical time scales at which information rate is acquired from the sampled signal and the stability of the signal's statistical properties over time.

The empirical category adopted in our study describes the potential interaction of a musical system in facilitating the categorization of IMSs according to the creation of compositional sonic architectures (Drummond, 2009). We subdivided empirical categories into dimensions to detail

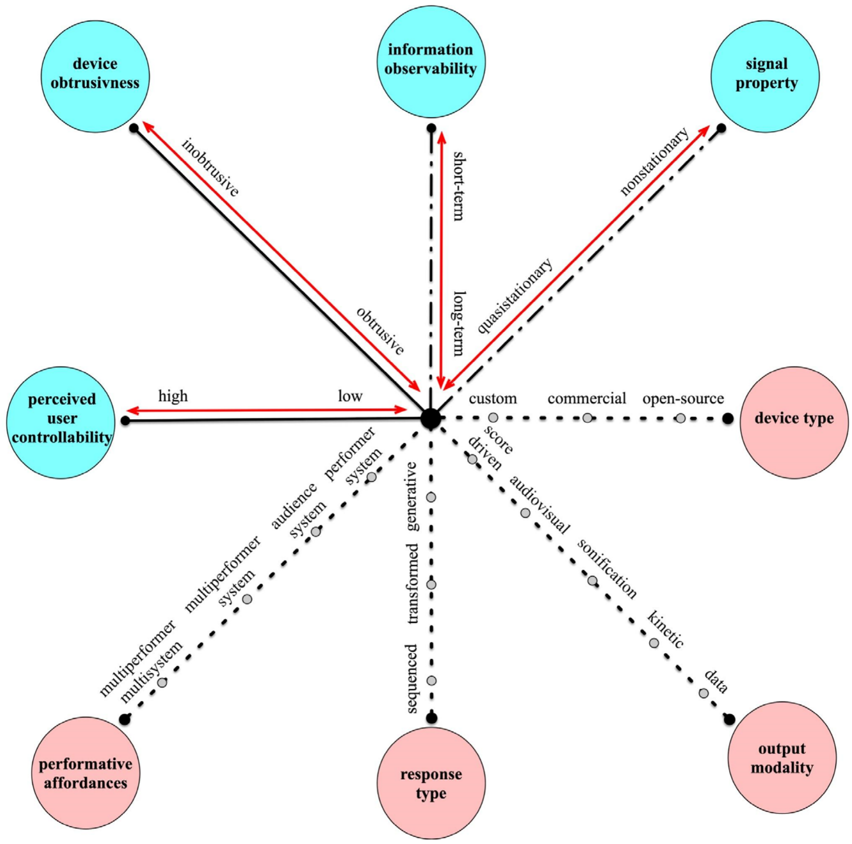

Figure 2. The functional and empirical categories in a dimensional space adopted in the IMS works' presented in Table 2 (see below). Here, we differentiated the functional and empirical categories by the colors blue and red, respectively. In the star diagram, each line from the center of the space denotes a different dimension, with line strokes identifying its area of knowledge: human–computer interaction (solid line), signal processing (dashed line), and interactive music system (dotted line). Dimensions in our taxonomy can be continuous or discrete. The continuous dimensions are denoted as (red) arrowed lines whose endpoints are identified as qualitative spaces.

biosignals as control structures from a technological perspective (device type) as well as their interactive musical qualities, such as output modality, response type, and performative affordances.

For example, we define the information observability of a biosignal as a temporal scale along with a continuous space whose limits are short-term and long-term observability. Depending on the application domain, long or short degrees of changes can promote different information rates. The discrete qualitative spaces designated with a gray circle along the dotted lines can be positioned along or within dimensions' lines. A specific IMS can belong to a single or to multiple types. For example, the type of output musical response of an IMS can be either generative or sequenced or adopt both strategies along the musical time, yet as separate entities. A hybrid degree of generative and sequenced responses cannot exist.

We detail in the following two subsections each of the functional and empirical dimensions in our taxonomy according to (a) its grounded area of knowledge, (b) its definition and associated concepts in the literature, (c) its dimensions, and (d) its associated sensing device.

Functional Dimension

The functional category comprises four dimensions: perceived user controllability, device obtrusiveness, information observability, and signal property. From an HCI perspective, the perceived user controllability dimension represents the perceived control accuracy a user has over the output of a biosignal (Wanderley & Orio, 2002). In other words, the perceived user controllability indicates the degree of control a user maintains in the action–reaction (i.e., input–output) loop of an interaction system. It exists as a continuous dimension between two types: high- and low-perceived user controllability. A high degree of perceived controllability encompasses responses that originate from the somatic portion of the peripheral nervous system that controls skeletal muscle and voluntary movements, such as arm muscle activation or limb displacement. Examples of biosensors that users typically perceive as having a high degree of controllability are the EMG, FLEX, and GYR. A middle degree of perceived controllability would reflect EEG signals that capture a mixture of signals with a relative degree of control movements, such as eye opening and closing, as well as involuntary activity, such as the level of focus or relaxation through measurements of alpha or beta waves, respectively (Ray & Cole, 1985). An IMS musician can explore these many correlations to enrich the IMS musical experience. A low degree of perceived controllability is linked to responses that originate from the sympathetic nervous system's activity and is associated with involuntary activities that increase energy expenditure and arousal levels, such as electro-dermal, temperature, or cardiac activity (Tahiroğlu, Drayson, & Erkut, 2008). Examples of biosensors typically perceived by the user as having low controllability are the ECG, EDA, and RESP.

Also from HCI perspective, the device obtrusiveness dimension (i.e., both sensor and the respective signal-processing device[1]) denotes the user's physical experiences of that specific technological device. It exists as a continuous dimension between two types: obtrusive and inobtrusive. An obtrusive device refers to a physical experience of a specific technological device that the user may perceive as uncomfortable (Hensel, Demiris, & Courtney, 2006). Biosensors perceived as having a high degree of obtrusiveness typically are worn or attached to the body, such as headsets with electrodes for capturing brain activity (Çiçek, 2015). In extreme cases, obtrusive devices can be invasive, that is, placed inside the body (Filas, 2013). Invasive methodologies include indwelling needles and wire electrodes inserted into the muscle tissue to extract information about the processes at the muscle membrane level (Rau, Schulte, & Disselhorst-Klug, 2004). At the opposite end of the scale are inobtrusive devices, referring to the miniaturization of monitoring devices and the potential for the noninvasive capture of biosignals (Van den Broeck & Westerink, 2009). An example of a control structure sharing the property of being inobtrusive is body temperature when captured through an (off-the-body) infrared camera that detects heat patterns in body tissues. A middle degree of obtrusiveness is likely to be associated with smartwatches or toolkits for biosignal acquisition (the latter being more obtrusive).

From a signal processing perspective, the biosignal information observability dimension denotes the time scale at which changes in the biosignal-captured data (beyond residual noise) are observed. The information observability dimension exists as a continuous dimension between two types: short-term and long-term. A short-term information observability implies a biosignal from which information is retrieved at the millisecond range. For example, an EMG conveys information from muscle electrical activity that can have sudden degrees of change at the sample level; typical sampling rates of 250 Hz (Open BCI) and 1000 Hz (BITalino) are assumed. A middle degree of biosignal information observability can be linked to an ECG and PPG, for example. These signals capture cardiac activity within the 300 ms to 1.5 s range (Alian & Shelley, 2014; Malmivuo & Plonsey, 1995). Long-term information observability implies a biosignal in which information rate is lower due to its smaller degree of change over time. A long-term information observability occurs within the seconds range. A representative long-term information observability example is the EDA, whose response time to stimuli typically ranges between 1 and 5 s (Boucsein, 2012).

Finally, the signal property dimension denotes how stable the signal statistical properties are over time. The signal property exists as a continuous dimension between two types: quasistationary and nonstationary. A quasistationary signal has nearly steady statistical properties, that is, might change very slowly over time. An example of a quasistationary biosignal is body temperature measurements: The human body does not present abrupt temperature changes. A middle degree of signal stability is reflected in a respiration measurement during physical effort. At the beginning of the exercise, the respiration rate will be quasistationary, but as the physical effort increases, the measurements will be nonstationary, reflecting an increased acceleration in the pulmonary activity. A nonstationary signal has expressive statistical variations over time (Escabi, 2005) as demonstrated as an EEG measuring sudden eye-blinks or EMG measuring spikes in the muscular activity.

When working with biosensing technologies, one must recognize the devices' sensitivity to external interferences. Due to the dynamic nature of some IMS applications, motion is a primary source of the artifacts. The feeble nature of bioelectrical signals (i.e., in the millivolt range for the ECG and EMG and the microvolt range for the EEG, EGG, and EOG), brisk and high-intensity movements can result in electrode displacement—even when the device is attached to the skin over the target area—which introduces noise in the signals. Force also influences the measurement in some sensors. For example, the EDA, which measures skin impedance, can suffer from variable artifacts when pressure is applied to the electrode (which changes the contact area between the electrode and the skin). Additionally, the crosstalk between adjacent recording muscle sites is not negligible when electrodes are located on muscles with different functions (antagonist pairs or muscles with one common and one different function). Electromagnetic noise (e.g., from a transformer or fluorescent light) also is prone to mask the signals of interest or even lead to erroneous measurements (i.e., from strong magnetic sources influence, e.g., MAG signals). Environmental factors, such as air conditioning or heating units, can influence control structures such as HUM and/or TEMP. Other external factors also may indirectly affect the control structures that are controlled by the nervous system. For example, EDA responses can be triggered by startling, unexpected events such as a mobile phone ringing.

Empirical Dimensions

We now describe the empirical category adopted in our catalog of IMSs. We split the information into four empirical dimensions: device type, output modality, response type, and performative affordances. Empirical dimensions focus on the interactions mediated by interactive systems and their interaction potential for facilitating the creation of music. For example, is an IMS designed to be played by one, two, or more performers, or even include the audience as a player? Is its audiovisual modality projected in a physical space? Are there symbolic instructions for a coplaying hardware synthesizer or just a direct sonification process? Is it a generative response type, transformative, or prerecorded sound? When combined with functional categories, the empirical categories provide a clearer critical view about IMSs as a whole.

The device type presents the range of biosensing devices applied in each artwork and encompasses three discrete types: custom, commercial, or open-source. In IMSs' early embodiment, custom devices with biosensors were pervasive; yet even contemporary IMS works employ creator-developed devices. Since 2010, however, commercial mobile biosensing devices have been available on the consumer market. The advantages of these new technologies include quick and easy positioning, wireless Bluetooth or Wi-Fi data transmission, easier mobility, and affordable pricing (Chabin, Gabriel, Haffen, Moulin, & Pazart, 2020). Commercial devices aimed at the consumer market include the Emotiv or Neurosky products, as well as reliable devices for research works, such as g.tech, Cognionics, or Neuro-electrics products. More recently, open-source devices have emerged onto the market. The advantages of open-source devices for research and artistic purposes include rapid assembling, integration, and prototyping with several programming languages. Moreover, open-source products do not maintain a commercial restriction over the biosignal data. BITalino (Da Silva, Guerreiro, Lourenço, Fred, & Martins, 2014) and OpenBCI (Durka et al., 2012) are examples of such devices.

The output modality dimension defines IMSs according to the many ways of outputting signals through actuators, that is, a transducer element that converts electrical energy into other physical quantities or displays. The output modality dimension encompasses five discrete types: score-driven, audiovisual, sonification, kinetic, and data. A score-driven output type implies an IMS with embedded knowledge of the overall predefined compositional structure and the ability to track the performer in real-time, accommodating subtle performance variations. An audiovisual output space implies an output such as light bulbs, light-emitting diodes (LEDs), liquid crystal displays (LCDs), or video projectors and lasers. A sonification output type indicates a direct mapping between a specific biosignal attribute and its respective sound parameter. A kinetic output space denotes vibrotactile displays, for example, loudspeakers or piezo buzzers that correlate to the sense of touch or small electric motors and solenoids to address an audience's kinesthetic awareness. Finally, a data output space implies collecting and analyzing biosignal data from performers to understand a specific musical task (e.g., the recordings of biosignal data and motion information to understand interpretative and affective information of a musical performance).

In the response type dimension, we adopted Drummond (2009) to classify how an IMS responds to its input (Rowe, 1992). The response type dimension encompasses three discrete types: generative, transformative, and sequenced. A generative type of response implies a system's self-creation is either independent of or influenced by an external input. Transformative techniques suggest an underlying algorithmic processing model and generation, including techniques such as filtering, transposing, delay, distortion, or granulation. Sequenced techniques refer to the playback of predefined musical instructions.

The performative affordances dimension categorizes the IMS according to the number and quality of the participating agents. Affordances do not take into account the underlying algorithms, processes, and expressiveness of the interactions taking place but rather the number and role of agents interacting with the IMS. The performative affordances dimension includes four categorical types: The human performer, the audience, computational system agents, and any configuration involving two or more of these agents. In the former category, whenever nonexpert performers, primarily from audiences, are participating agents in the IMS, we identified them as AUD (audiences).

BIOSENSING IN IMS: A TEMPORAL PERSPECTIVE

Table 2 presents a comprehensive historical record of biosignal driven IMS. In discussing the trends in this section, we flagged the IMSs with in-line text notation that provides an item number followed by the date, as noted on Table 2 (e.g., [Item 5; 1970]). The table's entries span chronologically from 1965 to 2019 and present biosensing as a control structure of the music performance with IMSs. To provide more than a simple textual catalog of IMSs, as in Table 2, we computed global statistics from the catalog data to extrapolate representative historical trends, as will be graphically depicted below. From all the categories presented in Table 2, we plotted dimensions that we considered the most representative of the evolution of biosignal-driven IMSs, in particular the empirical categorization and its respective dimensions: the type of biosignal used, the type of response expected from a specific IMS, and the affordances IMS musicians seek when conceiving an IMS.

We have identified three historical trends from this analysis: The first of one spanned 1965 to 1985; a second trend was detected from 1985 to 2005; and a third trend extends from 2005 to 2019. In the figures presented below, the column on the left shows the relative percentage of data in stacked columns, where the cumulative total of the stacked components within the columns always equals 100%. This column chart shows the part-to-whole proportions over time: For example, the column chart in Figure 3 shows which biosensing devices were used from 1965 to 2019. Although the column provides the historical scope, it is not easy to compare the relative size components that make up each column. For accuracy, then we present a stacked area chart on the right that, as in the example of Figure 3, shows the same progression and composition over time.

Table 2. A Catalog of 70 Biosensor-driven IMS Artworks, Compiled and Categorized According to the Proposed Taxonomy.

	Title	Year	Author	Control	Device Type	Output modality	Response Type	Performative Affordances	Perceived Controllability	Device Obtrusivness	Information Observability	Signal Property
[item 1]	**Music for a Solo Performer**	1965	Alvin Lucier	EEG	Custom	Sonification Kinetic	Generative	Performer System	Low	Obtrusive	Long-term	Quasistationary
[item 2]	**Spacecraft**	1967	Richard Teitelbaum	EEG	Custom	Score driven	Generative Transformative	Multiperformer System	Low	Obtrusive	Long-term	Quasistationary
[item 3]	**In Tune**	1968	Richard Teitelbaum	EEG	Custom	Score driven	Generative	Multiperformer System	Low	Obtrusive	Long-term	Quasistationary
[item 4]	**Ecology of the skin**	1970	David Rosenboom, Richard Teitelbaum	EEG	Custom	Score driven	Generative Transformative	Multiperformer System	Low	Obtrusive	Long-term	Quasistationary
[item 5]	**DIMI-T "Electroencephalophone"**	1970	Erkki Kurenniemi	EEG	Custom	Score driven	Generative	Performer System	Low	Obtrusive	Long-term	Quasistationary
[item 6]	**Environetic synthesizer**	1970	Woody Vasulka, Richard Lowenberg	EEG	Custom	Score driven	Generative	Performer System	Low	Obtrusive	Long-term	Quasistationary
[item 7]	**DIMI-S "Sexophone"**	1971	Erkki Kurenniemi	EDA	Custom	Score driven	Generative	Multiperformer System	Mid	Obtrusive	Mid-term	Quasistationary
[item 8]	**Corticalart I and II**	1971-1973	Roger Lafosse, Pierre Henry	EEG	Custom	Score driven	Transformative	Performer System	Low	Obtrusive	Long-term	Quasistationary
[item 9]	**Brain Wave Music**	1974	David Rosenboom, Richard Teitelbaum	EEG	Custom	Score driven	Transformative	Multiperformer System	Low	Obtrusive	Long-term	Quasistationary
[item 10]	**On Being Invisible I pt.1**	1976-77	David Rosenboom	EEG	Custom	Score driven	Transformative Sequenced	Performer System	Low	Obtrusive	Long-term	Quasistationary
[item 11]	**Clocker**	1978	Alvin Lucier	EDA	Custom	Score driven	Transformative	Performer System	Mid	Obtrusive	Mid-term	Quasistationary
[item 12]	**The Graphic Method Bicycle**	1979	Dick Raaymakers	ECG, RESP, EMG	Custom	Score driven	Transformative	Performer System	Mid and High	Obtrusive	Mid-term	Quasistationary Nonstationary
[item 13]	**HeartBeat:mb**	1981	Chris Janney, Sara Rudner	ECG, EMG	Commercial Transkinetics inc.	Score driven	Generative	Performer System	Mid and High	Obtrusive	Mid-term Short-term	Quasistationary Nonstationary
[item 14]	**Kagami**	1991	Atau Tanaka	EMG	Commercial BioMuse	Score driven	Transformative Sequenced	Performer System	High	Obtrusive	Short-term	Nonstationary
[item 15]	**Synesthesia**	1992	Rita Addison et al.	ECG, RESP, EMG	Custom	Audio-visual	Sequenced	Multiperformer System	Mid and High	Obtrusive	Mid-term Short-term	Quasistationary Nonstationary
[item 16]	**The Mnemonic Body**	1995-2001	Alan Dunning, Paul Woodrow	EEG	Commercial IBVA Brain Machines	Audio-visual	Generative	Audience System	Low	Obtrusive	Long-term	Quasistationary
[item 17]	**The Madhouse**	1995-2001	Alan Dunning, Paul Woodrow	EEG	Commercial IBVA Brain Machines	Audio-visual	Generative	Audience System	Low	Obtrusive Inobtrusive	Long-term	Quasistationary
[item 18]	**Dérive**	1995-2001	Alan Dunning, Paul Woodrow	EEG, ECG, TEMP	Commercial IBVA Brain Machines	Audio-visual	Generative	Audience System	Low and Mid	Obtrusive Inobtrusive	Mid-term Long-term	Quasistationary Nonstationary
[item 19]	**Body Degree Zero**	1995-2001	Alan Dunning, Paul Woodrow	EEG, EMG	Commercial IBVA Brain Machines	Audio-visual	Generative Transformative	Audience System	Low and High	Obtrusive Inobtrusive	Long-term Short-term	Quasistationary Nonstationary
[item 20]	**Conductor's Jacket**	1998	Teresa Marrin-Nakra, Rosalind Piccard	EMG	Custom	Score driven	Sequenced	Performer System	High	Obtrusive	Short-term	Nonstationary
[item 21]	**cubeLife**	1999	Greg Turner	ECG	Custom	Audio-visual	Transformative Sequenced	Performer System	Mid	Obtrusive	Mid-term	Quasistationary Nonstationary
[item 22]	**BIOS - Bidirectional Input/Output System**	2002	Thomas Tirel, Sven Hahne, Jaanis Garancs, Norman Muller	EEG	Custom	Audio-visual	Generative Transformative	Performer System	Low	Obtrusive	Long-term	Quasistationary Nonstationary
[item 23]	**Sensors Sonic Sights**	2003	Atau Tanaka, Cecile Babiole, Laurent Dailleau	EMG	BioMuse	Audio-visual	Generative Transformative	Multiperformer System	High	Obtrusive	Short-term	Nonstationary

(continued)

Table 2. A Catalog of 70 Biosensor-driven IMS Artworks, Compiled and Categorized According to the Proposed Taxonomy. (Continued)

	Title	Year	Author	Control	Device Type	Output modality	Response Type	Performative Affordances	Perceived Controllability	Device Obtrusivness	Information Observability	Signal Property
[item 24]	**Sitting.Breathing.Beating.[NOT] Thinking**	2004	Adam Overton	EEG, EMG, RESP	Custom	Score driven	Generative	Performer System	Low and Mid	Obtrusive	Long-term Short-term	Quasistationary Nonstationary
[item 25]	**Diamair**	2007	Miguel Angel Ortiz, Benjamin Knapp, Michael Arcon	EDA	Commercial ThoughtTec	Score driven	Generative Transformative	Performer System	Mid	Obtrusive	Mid-term	Quasistationary
[item 26]	**Carne**	2008	Miguel Angel Ortiz	EMG	Custom	Score driven	Transformative	Performer System	High	Obtrusive	Short-term	Nonstationary
[item 27]	**S&V**	2009	Miguel Angel Ortiz	ECG	Custom	Score driven	Generative Transformative	Multiperformer System	Mid	Obtrusive	Mid-term	Quasistationary
[item 28]	**The Multimodal Brain Orchestra**	2009	Sylvain Le Groux, Jonatas Manzolli, Paul FMJ Verschure	EEG	Commercial g.Tech	Audio-visual	Generative	Multiperformer System	Low	Obtrusive	Long-term	Quasistationary
[item 29]	**The subConch**	2009	Mats J. Sivertsen	EEG	Commercial Emotiv EPOC	Audio-visual	Generative	Performer System	Low	Obtrusive	Long-term	Quasistationary
[item 30]	**Music Sensors and Emotion**	2009	SARC	EMG	BioMuse	Score driven	Generative Transformative	Performer System	High	Obtrusive	Short-term	Nonstationary
[item 31]	**Dentro**	2010	Miguel Angel Ortiz	EEG, ECG	Custom	Sonification	Generative	Performer System	Low and Mid	Obtrusive	Long-term Mid-term	Quasistationary
[item 32]	**Mind Pool**	2010	Kiel Long, John Vines	EEG	Commercial Emotiv EPOC	Kinetic	Generative	Audience System	Low	Inobtrusive	Long-term	Quasistationary
[item 33]	**The Brain Noise Machine**	2010	Greg Kress	EEG	Commercial Neurosky EEG	Kinetic	Generative	Audience System	Low	Inobtrusive	Long-term	Quasistationary
[item 34]	**Staalhemel**	2010	Christoph DeBoeck	EEG	IMEC	Kinetic	Generative	Audience System	Low	Inobtrusive	Long-term	Quasistationary
[item 35]	**Unsound**	2011	Miguel Angel Ortiz	ECG, EDA	BioMuse	Audio-visual	Generative	Audience System	Mid	Obtrusive Inobtrusive	Mid-term	Quasistationary Nonstationary
[item 36]	**MoodMixer**	2011	Grace Leslie, Tim Mullen	EEG	Commercial Neurosky EEG	Score driven	Generative Sequenced	Audience System	Low	Non-obtrusive	Long-term	Quasistationary
[item 37]	**DECONcert**	2011	Steve Mann, James Fung, Ariel Garten	EEG	Commercial ThoughtTec	Score driven	Transformative	Audience System	Low	Non-obtrusive	Long-term	Quasistationary
[item 38]	**Music for Flesh I and II**	2011	Marco Donnarumma	MMG	Open source Xth Sense	Score driven	Generative Transformative	Performer System	High	Obtrusive	Short-term	Nonstationary
[item 39]	**Hypo Chrysos**	2011	Marco Donnarumma	MMG	Open source Xth Sense	Score driven	Generative	Performer System	High	Obtrusive	Short-term	Nonstationary
[item 40]	**The Warren**	2011	Joel Eaton	EEG	Custom	Score driven	Generative Transformative	Performer System	Low	Obtrusive	Long-term	Quasistationary
[item 41]	**Music for Sleeping and Waking Minds**	2011	BioMuse Trio	EEG	BioMuse	Score driven	Generative	Multiperformer System	Low	Obtrusive	Long-term	Quasistationary
[item 42]	**Brain Pulse Music**	2012	Masaki Batoh	EEG, ECG	Commercial Neurosky EEG	Audio-visual	Transformative	Performer System	Low Mid	Obtrusive	Long-term Mid-term	Quasistationary Nonstationary
[item 43]	**The Escalation of Mind**	2012	Vsevolod Taran	EEG	Commercial Emotiv EPOC	Audio-visual	Generative	Performer System	Low	Obtrusive	Long-term	Quasistationary
[item 44]	**Clasp Together (beta)**	2012	Harry Whalley, Panos Mavros, Peter Furniss	EEG, ECG, ACC	Commercial Emotiv EPOC	Score driven	Sequenced	Performer System	Low to High	Obtrusive	Pervasive	Quasistationary Nonstationary
[item 45]	**Omnious**	2012	Marco Donnarumma	MMG	Open source Xth Sense	Score driven	Generative Transformative	Performer System	High	Obtrusive	Short-term	Nonstationary
[item 46]	**The Moving Forest**	2012	Marco Donnarumma	MMG	Open source Xth Sense	Score driven	Generative Transformative	Performer System	High	Obtrusive	Short-term	Nonstationary

(continued)

Table 2. A Catalog of 70 Biosensor-driven IMS Artworks, Compiled and Categorized According to the Proposed Taxonomy. (Continued)

	Title	Year	Author	Control	Device Type	Output modality	Response Type	Performative Affordances	Perceived Controllability	Device Obtrusiv ness	Information Observability	Signal Property
[item 47]	**[radical] Signs of Life**	2013	Marco Donnarumma	PPG, MMG	Open source Xth Sense	Score driven	Generative Transformative	Performer System	Low High	Obtrusive	Short-term Mid-term	Quasistationary Nonstationary
[item 48]	**Alpha Lab**	2013	George Khut, James P. Brown	EEG	Commercial Myndplay	Sonfication	Generative	Audience System	Low	Inobtrusive	Long-term	Quasistationary
[item 49]	**(un)Focused**	2013	Alberto Novello	EEG	Commercial Emotiv EPOC	Audio-visual	Generative	Multiperformer System	Low	Obtrusive Inobtrusive	Long-term	Quasistationary
[item 50]	**The Space Between Us**	2014	Joel Eaton, Wei Wei Jin, Eduardo Reck Miranda	EEG	BioMuse	Score driven	Generative	Multiperformer System	Low	Obtrusive Inobtrusive	Long-term	Quasistationary
[item 51]	**Conductar**	2014	Jeff Crouse, Gary Gunn, Aramique	EEG	Commercial Neurosky EEG	Audio-visual	Generative	Audience System	Low	Inobtrusive	Long-term	Quasistationary
[item 52]	**eeg-deer**	2014	Dmitri Morozov	EEG	Modified Necomimi	Audio-visual	Generative	Performer System	Low	Obtrusive	Long-term	Quasistationary
[item 53]	**Fragmentation: a brain-controlled performance**	2014	Alberto Novello	EEG	Commercial Emotiv EPOC	Audio-visual	Generative	Performer System	Low	Obtrusive	Long-term	Quasistationary
[item 54]	**Activating Memory**	2015	Eduardo Reck Miranda, Joel Eaton	EEG	Commercial g.Tech	Sonification	Sequenced	Multiperformer System	Low	Obtrusive	Long-term	Quasistationary
[item 55]	**state.scape**	2015	Mirjana Prpa, Svetozar Miucin, Bernhard Riecke	EEG	Commercial Emotiv EPOC	Audio-visual	Generative	Performer System	Low	Obtrusive	Long-term	Quasistationary
[item 56]	**Deep Profundis**	2015	Davide Mancini, Simona Lisi	EEG	Soundmachines, Neurosky	Score driven	Generative	Performer System	Low	Obtrusive	Long-term	Quasistationary
[item 57]	**Vessels**	2015	Grace Leslie	EEG, ECG, EDA	Muse	Score driven	Generative Transformative	Performer System	Low Mid	Obtrusive	Long-term Mid-term	Quasistationary Nonstationary
[item 58]	**Eyes Awake**	2015	Grace Leslie, Carolyn Chen	EEG	Muse	Score driven	Generative Sequenced	Performer System	Low	Obtrusive	Long-term	Quasistationary
[item 59]	**Emotion in Motion**	2015	Benjamin Knapp, JavierJaimovich, Brennon Bortz	ECG, EDA	Custom	Data Recording	Sequenced	Audience System	Low Mid	Inobtrusive	Long-term Mid-term	Quasistationary Nonstationary
[item 60]	**Choreography and Composition of Internal Time**	2016	Teoma Naccarato, John MacCallum	ECG	Custom	Score driven	Generative Sequenced	Performer System	Low Mid	Obtrusive	Mid-term	Quasistationary Nonstationary
[item 61]	**Behind Your Eyes, Between Your Ears**	2016	George Khut	EEG	Muse	Audio-visual	Generative	Audience System	Low	Obtrusive	Long-term	Quasistationary
[item 62]	**Corpus Nil**	2016	Marco Donnarumma	EMG, MMG	Open source Xth Sense	Score driven	Generative Transformative	Performer System	High	Obtrusive	Short-term	Nonstationary
[item 63]	**E.E.G. Kiss**	2016	Karen Lancel, Herman Maat	EEG	IMEC, Muse	Audio-visual	Generative Sequenced	Audience System	Low	Obtrusive	Long-term	Quasistationary
[item 64]	**Noor: a Brain Opera**	2016	Ellen Pearlman	EEG	Commercial Emotiv EPOC	Score driven	Sequenced Transformative	Performer System	Low	Obtrusive	Long-term	Quasistationary
[item 65]	**Synchronism**	2016	Teoma Naccarato, John MacCallum	EEG	Custom	Score driven	Generative Transformative	Performer System	Low	Obtrusive	Long-term	Quasistationary
[item 66]	**Tangente**	2017	Teoma Naccarato, John MacCallum	ECG	Custom	Score driven	Generative Sequenced	Performer System	Mid	Obtrusive	Mid-term	Nonstationary
[item 67]	**Harmonic Dissonance**	2018	Mathias Oostrik, Suzanne Dikker	EEG, EDA	Commercial Emotiv EPOC	Audio-visual	Generative	Multiperformer System	Low Mid	Obtrusive	Long-term Mid-term	Quasistationary Nonstationary
[item 68]	**Alia: Zu tai**	2018	Marco Donnarumma	MMG	Open source Xth Sense	Score driven	Generative Transformative	Multiperformer System	High	Obtrusive Inobtrusive	Short-term	Nonstationary
[item 69]	**Eingeweide**	2018	Marco Donnarumma	MMG	Open source Xth Sense	Score driven	Generative Transformative	Multiperformer System	High	Obtrusive	Short-term	Nonstationary
[item 70]	**Vrengt**	2019	Cagri Erdem, Katja Henriksen Schia, Alexander Refsum Jensius	EMG	Commercial Myo	Score driven	Generative Transformative	Performer System	High	Obtrusive	Short-term	Nonstationary

The first historical phase, from 1965 to 1985, involved a small group of early adopters of biosignal-driven IMSs and is explained by the novelty of biosensing as a means of control and interaction within IMSs. Spanning the years 1985 to 2005, the second historical phase was marked by a decrease in the use of biosensors during the late 1980s but a resurgence in IMS practices in the 1990s. Finally, the third historical phase, from 2005 and 2019, encompasses a major appropriation of biosensors. A healthy growth in the availability of open-source devices can explain this, supplemented by the introduction of wearable technology that facilitated the logistics for installing, running, and repeating a specific biosignal-driven IMS in various performative contexts.

In the next subsections, we detail a critical overview of the results computed to extrapolate representative historical trends. Thus, we interpreted the statistics of each identified historical phase, as well as their representative IMSs.

Biosensing in IMS: A Critical Overview

By computing global statistics from the catalog data, we extrapolated representatives to identify historical trends. In Figure 3, EEG sensors prevailed across biosensor-driven IMSs, featured in 55.9% of the IMSs listed in Table 2. We believe that the more extensive adoption of EEG sensor technology in IMSs was related to their expressive adoption by the pioneers with the goal of achieving incorporeal communication channels between the brain and the artistic feedback manifestation. Furthermore, it reflected the ancient human desire embodied in myths and magical characters for controlling and taking action on the physical world manifestation with the brain.

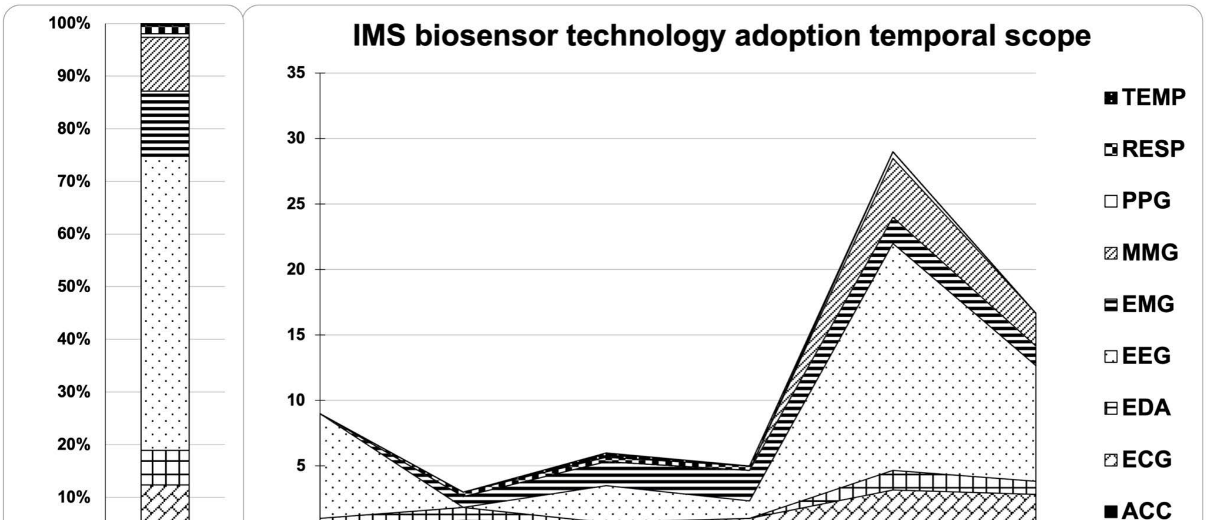

Figure 3. A global statistics visualization of the biosensors' appropriation within IMSs, 1965−2019. Abbreviations: ACC (accelerometer), AF (air flow), AP (air pressure), ECG (electrocardiogram), EDA (electrodermal activity), EEG (electroencephalogram), EGG (electrogastrogram), EMG (electromyogram), EOG (electrooculogram), FSR (force sensors), FLEX (flex sensors), GYR (gyroscope), MMG (mechanomyography), HUM (humidity), MOCAP (motion tracking), PST (position), PPG (photoplesmography), RESP (respiration), and TEMP (temperature).

The remaining types of sensor appropriated into IMSs per frequency of adoption are EMG (12.5%), ECG (11.8%), MMG (10.2%), and EDA (6.6%) sensors. The latter set of sensors captures muscle movements (limbs and heart) and skin conductance resulting from sympathetic nervous system activity. EMG and MMG sensors promote a voluntary control of the feedback, aligned with the typical fine degree of control fostered by instrumental practice. Meanwhile, EDA and ECG sensors enforce the impact of external conditions to act indirectly, pervasively, and repeatedly on the control structures via their embodiment in the performer. Biosensing technologies such as PPG, RESP, TEMP and ACC have a residual appropriation in IMSs, featured in only 3% of the IMSs of that era. Finally, AF, AP, EGG, EOG, FSR, BSR, GYR, HUM, MOCAP and PST biosensors were not identified in any IMS works between 1965 and 1985. This fact is due presumably to the technical difficulties. For example, EOG implies the use of fixed cameras that reduces the scope of eye movement detection to fixed positions. Sensors such as HUM have a prolonged signal evolution not fitting into the temporal span of a musical performance.

Another example is the low-level appropriation of the EGG sensor that captures the electrical signals in the stomach muscles. Because limb movements are more expressive in musical practice, sensors such as EEG were overridden by EMG and MMG sensors, which are more prominent in IMSs. A compelling case is the low level of appropriation of GYR and ACC sensors. GYR and ACC are ubiquitous sensors, although we did not note any IMS appropriating these types of sensors exclusively. Rather, our catalog of IMSs showed their use only in conjunction with adjacent sensors, for example, EMG sensors for a complete panorama of limb movement.

With advancements in areas of knowledge such as machine learning and software applications capable of dealing with large amounts of data, we envision a higher degree of appropriation of these less used sensors in IMSs. Cross-referencing the data from these sensors with other sensors, such as the EMG, will expand the scope of biosignal readings for a complete embodiment in IMS practices.

The temporal trend of appropriation of biosensors in IMS indicated in the right graph of Figure 3 shows that EEG sensors have prevailed since 1965 as a preeminent control structure in IMSs. However, since 1995, the EMG has peaked as a control structure for IMSs, owing mainly to a very productive practices of Tanaka and Donnarumma, whose IMSs are muscle-based. Moreover, the temporal peak in EMG use as a signal source presumably correlate with faster computers able to perform operations at faster sample rates. Despite technological improvement and artistic practices, EDA and ECG sensors tend to maintain a continuous baseline in terms of appropriation.

Figure 4 shows the type of response of IMSs across generative, transformative, or sequenced categories. We identified that 62.1% of the listed IMSs featured a generative response, followed by 25.5% of transformative responses, and 12.4% sequenced responses. The prevalence of generative responses indicates the growing trend toward cognitive-enhanced IMSs. Such systems typically embed levels of higher unpredictability and reflect the growing interest in cocreative systems involving computer programs collaborating with human musicians on creative tasks (Karimi, Grace, Maher, & Davis, 2018). As indicated in the main graph in Figure 4, the generative type of response prevails across the IMSs listed in our catalog. This comprehensive approach reveals in a more transparent way the concept of interactive composing introduced in our Introduction. However, we also witnessed a rise in IMSs employing a transformative type of

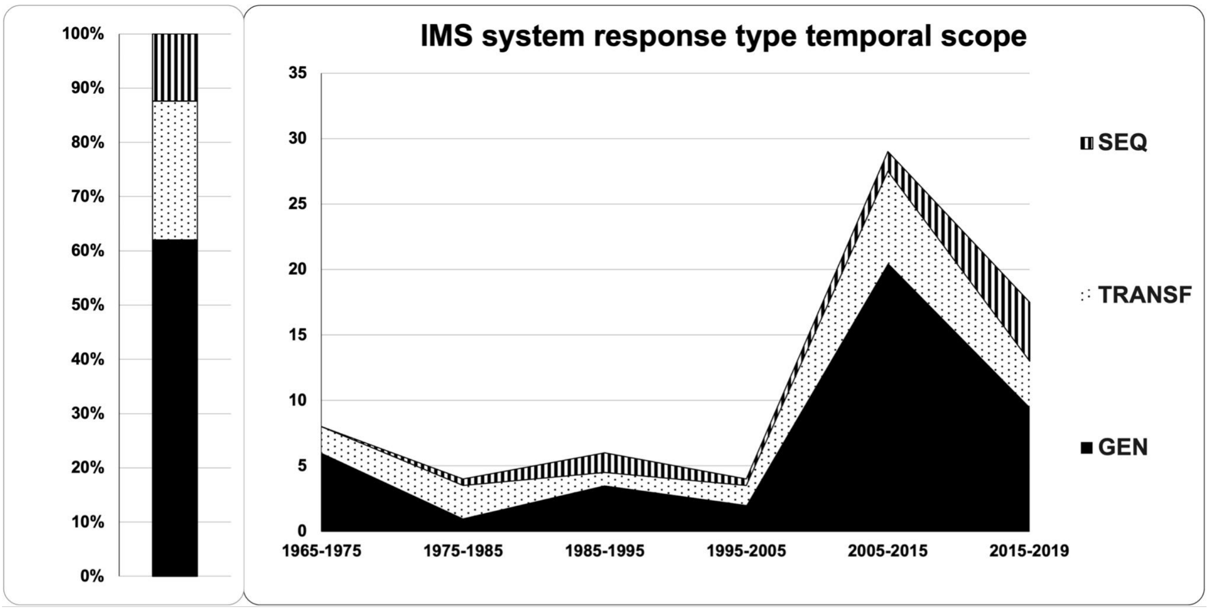

Figure 4. A global statistics visualization of the system response in biosensor-driven IMSs. Abbreviations: GEN (generative) implies the system's self-creation that is either independent of or influenced by an external input; TRANSF (transformative) suggests an underlying algorithmic processing model, including techniques such as filtering, transposing, delay, distortion, or granulation; and SEQ (sequenced) refers to the playback of predefined musical instructions.

response. We understand the rise of transformative types of response as a natural outgrowth of contemporary sophistication of algorithms for live sound processing that offer almost unlimited possibilities to design, create, and mix an outstanding real-time immersive experience.

Finally, Figure 5 shows the type of affordances a biosensor-driven IMS features. Of all IMSs analyzed, 55.7% were designed for one performer and one IMS. This expressive value highlights the advanced expertise required to develop these systems and their expressive appropriation to be confined somehow to the community of techno-fluent artists. Most artists opted for developing a biosensor-driven IMS for self-expression. Interestingly, we see that 21.4% of the analyzed works report an interaction between one system and the audience, meaning that a coshared control of the IMS presumably was due to the interest of IMS artists to include the audience in the understanding of the artwork. Thus, a multiperformer and a biosensor system had relevance in the cases analyzed, with 14.3%, especially those IMSs that included musical ensembles. Finally, 8.6% of all cases analyzed denoted an affordance of multiperformer/multisystem set up. We suggest the trend in Figure 5—with IMSs reflecting multiperformer with multisystems—probably indicates a growing interest of artists in performing pieces that can communicate remotely. Advancements in interconnectivity and bandwidth velocity promote IMSs that share control in a collaborative form, fostering the social impact that multiperformer and multisystem IMS artworks can have in the near future of musical practices.

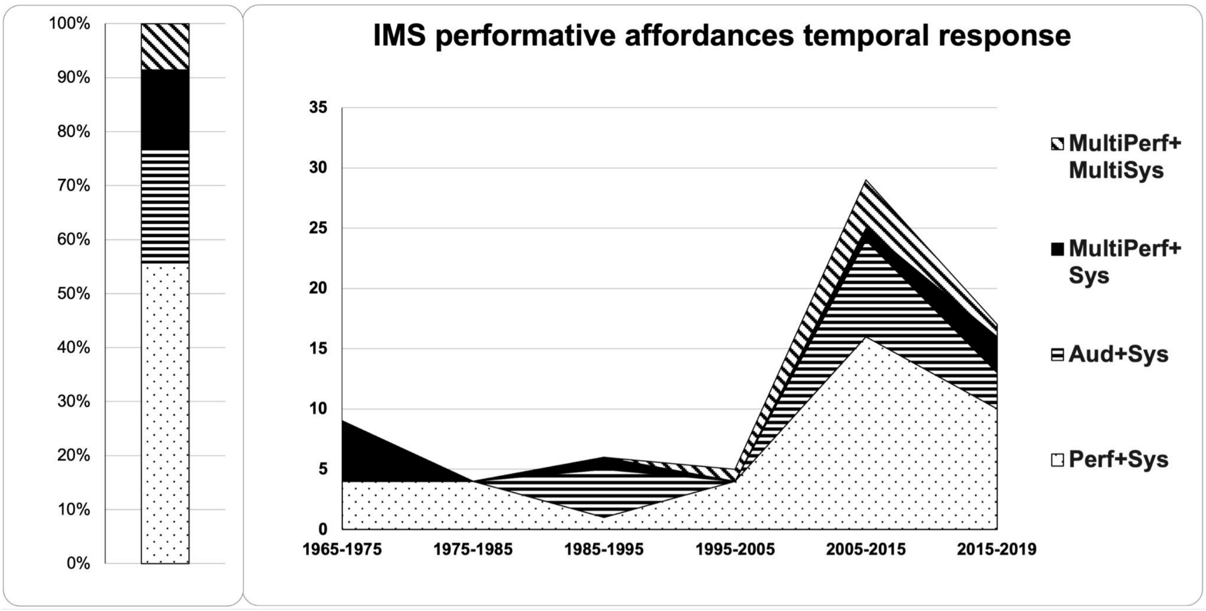

Figure 5. A stacked chart visualization of affordances in biosensor-driven IMS. Abbreviations: PERF+SYS (human performer plus computational system), AUD+SYS (audience plus computational system), MULTIPERF+SYS (multiple human performers plus computational system), and MULTIPERF+MULTISYS (multiple human performers plus multiple computational systems).

First Practices: 1965 to 1985

From 1960 to 1985, the first practices with biosensors in IMSs emerged. Through these early practices, composers sought to create incorporeal experiences of musical gestures by adopting as control structures the brain's electrical activity from electrodes placed in direct contact with the scalp. A direct translation of cortex waves into raw signals then was mapped to actuator parameters in physical and electronic music instruments, promoting feedback within IMSs. The prominent use of the EEG was to establish an immaterial connection between control and feedback. At that time, brain wave signals typically were mapped in a one-to-one fashion to actuators via electrical voltage control. Servomotors that actuate physical musical instruments and analogue synthesizers controlled via amplified brain wave signals were adopted. The biosensor technologies of that era were primarily medical setup devices that underwent several stages of customization to comply with performative musical settings such as *Music for a Solo Performer* (Holmes, 2012).

Lucier's *Music for a Solo Performer* [Item 1; 1965; Lucier, 1976; Straebel & Thoben, 2014] premiered in 1965 at the Rose Art Museum of Brandeis University in Waltham, Massachusetts, USA, and is the first musical piece composed and performed using brain waves, namely alpha waves in the range of 8-12 Hz. The artist's own brain waves controlled a series of servomotor actuators on percussion instruments, namely snares, cymbals, and gongs. Shortly after that, Teitlebaum wrote the improvisational musical pieces, *Spacecraft* [Item 2; 1967/68) and *In Tune* [Item 3; 1967/68], consisting of biofeedback circuitry to process amplified alpha brain waves. The signal was mapped to specific parameter controls of a custom Moog synthesizer via control voltages. Erkki Kurenniemi built the *DIMI-T Electroencephalophone* [Item 5; 1970], an electronic unit that registered a weak EEG signal from the user's earlobe. The biosignal was filtered, amplified, and used as a control source for a voltage-controlled oscillator. He later built the *DIMI-S Sexophone* [Item 7; 1971], a six-performer version of the DIMI-T, where handcuffs and wires connected the performers to the central electronic unit that measured the electrical resistance between all six performers. A sequence of musical tones was heard when two performers touched each other's hands repeatedly; the intensity of the music increased when skin moisture was elevated. Woody Vasulka and Richard Lowenberg created the *Environetic synthesiser* [Item 6; 1970] as a collaborative effort to incorporate the newest information technologies from biomedical engineering, psychophysiology, computer video display, and electronic music synthesis within a framework of a comprehensive art−communications system theory.

Henry and Lafosse collaborated on two experimental music albums, namely *Mise en musique du Corticalart I* and *Corticalart II* [Item 8; 1971; Arslan et al., 2005], consisting of the transcription of electric cortex waves into raw signals to control prerecorded audio samples. Between years 1974 and 1977, Teitlebaum and Rosenboom first produced *BrainWave Music* [Item 9; 1974], a piece informed by each of the performer's biosignal responses and, later, *On Being Invisible Pt.1* [Item 10; 1976−1977], a piece for a solo body, brain waves, and a computer-assisted music system. One common feature on these works was that a performer operated the system controls. However, in Teitlebaum and Rosenboom's earlier composition, *Ecology of The Skin* [Item 4; 1970], the system control was shared among the performer and the audience. Alvin Lucier created *Clocker* [Item 11; 1978], consisting of a contact microphone placed in a clock capturing the sound of the ticks. The audio then was routed through a digital delay unit that had a controlled delay time through the output voltage of an EDA. The changes in skin resistance produced corresponding changes in voltage, causing the ticks of the clock to slow down and speed up. *The Graphic Method Bicycle* [Item 12; 1979] is a Dick Raaymakers performance aimed at recording what happens when one tries to bring back to life a video-recorded movement—in this case, a man getting off a bicycle. Biosensors monitor his heart, breathing, and muscular and emotional activity during the dismounting action, and the acoustic signals were amplified and loudly transmitted to the audience. Chris Janney and Sara Rudner created *HeartBeat:mb* [Item 13; 1981]. Their biosensing device, developed by Transkinetics, Inc., captured electrical impulses of the performer's heart and surrounding muscles via wireless telemetry. The gathered data, amplified through filters and a sound system, provided a percussive track layered over music, such as a jazz scat, Indian tabla rhythms, and Chris Janney's recitation of medical texts.

Modern Practices: 1985 to 2005

Despite the increase in the computational power, storage capacity, and enhanced digital signal processing methods, we observed that, during the 1980s, few to none of the documented works appropriated biosensors as control structures in IMSs. The low adherence is possibly due to the musicians' awareness of the complexity of the brain signal and the limitations of the analytical tools in extracting relevant features from the noisy biosensor technology at the time. Drawing on the novel advances in brain-controlled interfaces, a new wave of biosensor-driven IMSs emerged in the 2000s. Interoperability among several computational and human agents within IMSs and the increased degree of transparency in the hardware components equally promoted new approaches to an established practice within IMSs. Computational power—and especially miniaturization—gave rise to several IMSs binding biosensors more seamlessly with more sophisticated mapping strategies. The technological context fostered the development of the

BioMuse system as a musical instrument based on physiological biosensing. The BioMuse system used EEG, ECG and EMG sensor data that became the human interface data as well as the articulation of computer processes such as digital audio and computer graphics (Lusted & Knapp, 1996).

The Bio-Muse system was used in IMS pieces such as Tanaka's *Kagami* [Item 14; 1991], which afforded a way to control music programs (and therefore compose) by tensing and relaxing the arm muscles. Addison developed an interactive artwork project, *Synesthesia* [Item 15; 1992], where the researchers employed individual ECG, RESP, and EMG measurements to create and drive a virtual reality environment. First, they acquired a participant's heartbeat and then fed it back to a sonification system and outputted it as a recognizable sound. Then they switched signals (auditory to visual). The project director's creative endeavor drew on her interest in brain trauma resulting from her injuries suffered in an automobile accident. Within the immersive, real-time virtual reality environments, participants could fill the multisensory "gaps" via "invisible" interaction/networking. Thus, some of the networking was energized through proprioceptive and kinesthetic dynamics.

Dunning and Woodrow developed a cycle of installations *The Mnemonic Body* [Item 16; 2002], *The Madhouse* [Item 17; 2001], *Derive* [Item 18; 2001], and *Body Degree Zero* [Item 19; 2004]. These authors invited participants to touch, stroke, and breathe upon particular locations of a life-size cast of a male human body to produce corresponding images and sounds in the main virtual world. In addition, electrodes gathered the participants' brain waves, which then were fed in real-time into a three-dimensional virtual reality environment. This process manifested visual and aural equivalents that then were projected onto a second screen and amplified into the physical space of the presentation.

The Conductor Jacket [Item 20; 1998; Marrin & Picard, 1998] was presented as a device able to collect and analyze data from conductors. The conductors recorded physiological and motion information from musicians with the goal of understanding better how they expressed affective and interpretive information while performing. Dave Everitt and interaction designer Greg Turner created an artwork driven by a heartbeat monitor, called *cubeLife* [Item 21; 1999]. This artwork was based in a virtual world populated by magic cubes (i.e., one kind of matrix in three dimensions) created through a heartbeat sensor of the participants' input either online or in the exhibition space. Each cube had a finite lifespan and associated sound and inhabited an artificial life environment where it could be made to flock with other cubes or follow various defined behaviors. Colors and variations were chosen from an inbuilt color harmony system or preprogrammed by the performers for particular effects. Media artist Marco Donnarumma (2001) presented *Music for Flesh I and II* [Item 38; 2001], an interactive sound art performance. The piece was performed in a concert setting with a circular array of subwoofers and loudspeakers. The work created a seamless mediation between human bioacoustics and algorithmic composition using the Xth Sense, a biophysical musical instrument created by Donnarumma.

The *BIOS—Bidirectional Input/Output System* [Item 22; 2002] collective involved participants in a collaborative project of interactive audio−visual and technological disciplines, resulting in several projects involving interactive 3D, audio−visual creations, and virtual reality. *Sensor Sonic Sights* [Item 23; 2003] was an audio−visual performance composed by Tanaka, Babiole, and Dailleau that explored gesture expressivity through the use of EMG sensors as a control structure for generating visual and sound synthesis. Overton's *Sitting Breathing [NOT Thinking;* Item 24; 2004] occurred during seven afternoons of seated meditation, with EEG, ECG, and RESP biosensors and interactive sound software. The performer's breaths, heartbeats, and brain waves manipulated digital sound in real-time, exposing the dynamic relationships between these continuously evolving, internal systems.

Contemporary Practices: 2005 to 2019

As the third phase generally started in 2005, the wide availability of numerous affordable EEG headsets increased the artistic experimentation with brain signals. Devices such as ThoughtTec, Neurotech's Emotiv Epoc, and Neurosky were delivered with proprietary software for estimating levels of meditation and excitement. Despite the weaker signal-to-noise ratio of these commercial devices as compared to medical biosensing devices, some IMS musicians appropriated noise as a control source of an IMS (Vavarella, 2015). For example, eye blinking when taking EEG measures is considered noise even though, in artistic contexts, this by-product can be turned into a control structure for a biosignal-driven IMS. Today, we have witnessed an increase in the level of information extracted from the biosensors. IMSs yield a high-level understanding from biosignals by evoking emotional, cognitive, and collaborative dimensions across participating agents.

More than two thirds of the IMSs identified in our study were created after 2005. Ortiz created *Díamar* [Item 25; 2007] as an Integral Music Controller (IMC) for compositional purposes. The IMC enables traditional musical control, such as singing and conducting, to co-occur with augmented and remote gestural interaction through EMGs. The artist continued exploring IMSs through biosignal interaction (Ortiz, 2021). *Carne* [Item 26; 2008] was written for an amplified violoncello and EMG sensors and was inspired by Terry Bison's 1991 short story, "They're Made Out of Meat." *S&V* [Item 27; 2008] was a piece that explored the non-real-time usage of biosignals to generate musical materials. In *S&V*, ECG signals were employed as an instrument to produce or manipulate sounds directly; in addition, prerecorded data sets of ECG signals were used to generate musical materials such as melodic and rhythmic patterns. The aim was to explore these signals in a more structured way while still using the heart as an instrument in real time. Ortiz also created *Dentro* [Item 31; 2010] as an IMS work composed for EEG and ECG as a homage to Alvin Lucier's *Music for Solo Performer*. The performer undergoes several emotional and cognitive states throughout the piece. In *Unsound* [Item 35; 2011], Ortiz teamed with the Sonic Arts Research Centre to develop a system for real-time tracking of audience members' emotional responses. Based on ECG and EDA measurements, the short film *Unsound* had both dynamic musical score and visuals according to the recorded biosignals. The *Multi-modal Brain Orchestra* [Item 28; 2009] explored the question of what creative content a collection of brains can generate when directly interfaced with the world, that is, bypassing their physical bodies. The orchestra members played virtual musical instruments through EEG interface technology while emotion analysis drove the affective content of a multimodal composition. The emotional input resulted in an interplay of the brain as both an actor and an observer of its actions. *The subConch* [Item 29; 2009] was an interactive installation by Sivertsen that addressed both phenomenological and textual aspects integrated with technology involving the use of EEG sensors to allow a participant cognitive control over sound and light, thereby producing a multidimensional aesthetic experience.

Music Sensors and Emotion [Item 30; 2009] was a study conducted by Knapp, Jaimovich, and Coghlan. Using physiological and kinematic sensors, the composers undertook a direct measurement of physical gestures and emotional changes in a live musical performance. These composers developed an IMC by using both motion and emotion to control sound generation. Long and Vines presented *Mind Pool* [Item 32; 2010] as an interactive BCI artwork that provided real-time feedback of brain activity to those interacting with it. Brain activity was represented sonically and physically via a magnetically reactive liquid placed in a pool in front of the participant; the liquid encouraged interaction and self-reflection by motivating participants to relate the ambiguous feedback with their brain activity. *Brain Machine* [Item 33; 2010] was a brain-controlled kinetic sculpture operated by mental energy, and the machine created a continuous stream of chaotic noise. When a high level of mental focus was detected, the device felt silent and remained in that state as long as the user could maintain focus. De Boeck created *Staalhemel* [Item 34; 2010], an intimate metaphor for the topography of the brain laid across a grid of 80 steel ceiling tiles as a spatialized form of tapping. The visitor experienced the dynamics of his/her cognitive self by, when fitted with a wireless EEG interface, walking under the acoustic representation of his/her brain waves. The accumulating resonances of impacted steel sheets generated penetrating overtones. The spatial distribution of impact and the overlapping of reverberations created a very physical sound space to house an intangible stream of consciousness.

MoodMixer [Item 36; 2011] was an interactive installation authored by Grace Leslie. *Mood Mixer* invited participants to navigate collaboratively a two-dimensional music space by manipulating their cognitive state and conveying this state via wearable EEG technology. Mann, Fungen, and Garten presented *DECOncert* [Item 37; 2011], a study in which participants immersed in water and connected to EEG equipment could create or affect live music by varying their alpha wave output. The authors explored the five states of matter—namely solid, liquid, gas, plasma, and quintessence—in the context of immersive media within a specific state of matter. Some of these immersive environments spanned multiple countries by way of networked connectivity.

Media artist Marco Donnarumma presented *Hypo Chrysos* [Item 39; 2011], *Omnious* [Item 45; 2012], *The Moving Forest* [Item 46; 2012], and *radical Signs of Life* [Item 47; 2013] as a series of pieces that explored interactive sound art performances for human bioacoustics and algorithms using the Xth Sense (Donnarumma, 2011), a biophysical musical instrument created by the author.

Eaton's piece *The Warren* [Item 40; 2011] employed an EEG machine and a technique called steady-state visually evoked potentials (SSVEPs), the natural response signals to visual stimulation at specific frequencies. In this artwork, SSVEPs allowed a user to select commands by looking at one of four icons on a computer screen that are flashing at different speeds. The more the user concentrated his/her gaze on an icon, the higher the brain signal reading for that command became. In turn, the signal was fed back to the icons to provide visual feedback to the user. The icons were mapped to musical parameters and commands relative to the composition. Through playing, ordering, timing, and sequencing how icons are played, the piece was controlled by the triggering sounds or individual parameters of controlled sound synthesis and effects. Knapp, Lyon, and DuBois conceived *Music for Sleeping and Waking Minds* [Item 41; 2011–2012], an overnight concert in which four performers fall asleep while wearing EEG sensors. The data gathered from these sensors were applied in real time to audio- and image-signal processing, resulting in a continuously evolving multichannel sound environment and visual projection.

Audiovisual installations, or performances, were very prominent in the years 2011−2013, with works such as Masaki Batoh's *Brain Pulse Music* [Item 42; 2012] and Vsevolod Taran's *The Escalation of Mind* [item 43; 2012]. In the former, the author realized a long-held dream of controlling the musical parameters via brain waves of several improvised pieces featuring traditional Japanese instruments. In the latter, the author conceived a performance in which the human brain served as a controlled voltage generator to render audiovisual transitions. At the heart of *The Escalation of Mind*, an actor cited fragments from Herman Hesse's *The Glass Bead Gam*e. During this process, the actor's brain wave activity, emotional state, and facial expressions are monitored in real time and combined with a synthesis of sound and video imagery, thus creating a unified environment in a virtual space. Whaley, Mavros, and Furniss presented a study, *Clasp Together: Composing for Mind and Machine* [Item 44; 2012; Whalley, Mavros, & Furniss, 2014] that explored questions of agency, control, interaction, and the embodied nature of musical performance within HCI. The piece was composed for small ensembles and live electronics. The composition departed from the traditional composer/performer paradigm by including both noninstrumental physical gestures and cognitive or emotive instructions integrated interactively into the score.

Combining neurofeedback training with participatory art and electronic music, Knut created *AlphaLab* [Item 48; 2013] to explore the possibilities of electronic art that entwined attention, experience, and compositional form. Participants rested on their backs on specially designed beds fitted with vibrotactile subbass speakers that augmented the biofeedback sound they heard in their headphones with low-frequency vibrations into the back of their bodies. Electronic soundscapes controlled by changes in alpha brain wave activity were used to guide participants to a place of intense but wakeful stillness.

The Space Between Us [Item 50; 2014] was a live musical performance in which the performers read an electronic score on a computer screen while the music this presented was generated by the emotions of a singer and an audience member. Both the singer and the audience member were wired to a BCI system. The system searched for emotional indicators in the brain waves and then predicted the participants' moods to control the musical score.

Conductar [Item 51; 2014] was an experience created by Crouse at Moogfest and afforded visitors an opportunity to physically wander the American city of Asheville, North Carolina and conduct a generative audio−visual world through movement and their neurological response to the environment. The audio−visual installation ran on a mobile app connected to a brain wave sensor. As participants strolled through the city, they would collectively compose new music with the electrical activity of their brains (via EEG data).

In Novello's *(un)Focused* [Item 49; 2013], brain waves were translated into laser shapes and sound; in *Fragmentation: A Brain-Controlled Performance* [Item 53; 2014], by the same composer, the performer controlled an avatar that was trying to escape a maze and whose movements generated visuals and sound. *Activating Memory* [Item 54; 2015] was a live music performance for a brain wave quartet and a string quartet codeveloped by Eaton and Miranda. *Activating Memory* was built as a BCI system to provide a new platform for users with motor disabilities to control musical instruments and to interact and communicate with each other through music.

Both Morozov's *eeg deer* [Item 52; 2014] and Prpa's *state.scape* [Item 55; 2015] were conceived as artwork installations where audio−visuals were generated from users' affective states (e.g., engagement, excitement, and meditation). The installations relied on an EEG interface-based virtual environment and sonification, both which served as platforms for the exploration of users' affective states in a responsive art installation.

In 2015, the Soundmachines BI1 braininterface was the first commercially available brain wave-to-synthesizer interface. The device was used in *Deep Profundis* [Item 56; 2015], created by Mancini in collaboration with the dancer Simona Lisi, to create the sound score for the dance choreography. Grace Leslie created two pieces. The first piece, *Vessels* [Item 57; 2015], was a brain−body performance that combined a flute and electronics improvisation with EEG sonification. The artist used recorded raw EEG, EDA, and ECG signals to actuate sound samples recorded from a flute and a voice. In the second piece, *Eyes Awake* [Item 58; 2015], created in collaboration with Carolyn Chen, Grace listened to her partner's guided meditation and, through the monitoring alpha rhythms pulsation, created a generative electroacoustic musical composition with a video overlay. *Emotion in Motion* [Item 59; 2015; Bortz, Jaimovich, & Knapp, 2015] was a framework created for the development of multiple emotional, musical, and biomusical interactions with collocated or remote participants. It was an open-source framework involving hardware-agnostic sensor inputs, physiological signal processing tools, a public database of data collected during various instantiations of applications built on the framework, and a Web-based application as front end and back end.

In 2016, Donnarumma presented *Corpus Nil* [Item 62; 2016], a performance for a human body and an artificial intelligence machine. In this piece, Donnarumma reflected the entire human body embodied with hardware and software through biosensing technology. Biosensors connected to the performer's limbs captured electrical voltages from the performer's body as well as corporeal sounds, all of which were mapped to various parameters of the IMS. Through a set of custom artificial intelligence algorithms, each bodily motion set was mapped to a sound and light event directed by the IMS.

Naccarato and MacCallum (2016, 2017) collaborated in a biosensing IMS artistic project that examined the use of real-time heart rate data from contemporary dancers to drive a poly-temporal composition for instrumental ensemble with live electronics. In *Choreography and Composition of Internal Time* [Item 60; 2016], the creators explored both the external expression and internal state of each dancer—physical, emotional, and psychological—in order to drive intentional arcs in heart activity over time. ECG data from the dancers provided an underlying clock for each musician, producing dynamic textures of time in the poly-temporal score. *Synchronism* [Item 65; 2016] was a participatory installation within a gallery involving three simultaneous invitations to the public: (a) a one-to-one performance where individuals joined the performer, one at a time, inside a private booth and shared via electronic stethoscopes and transducers the rhythms of their heartbeats in real time, stimulating sites of pulsation on their own and one another's bodies; (b) a multichannel, spatialized audio installation where bodies' cardiac, respiratory, and fluid sounds were rendered; and (c) a labyrinth-like paper kinetic sculpture installed in the public space. Several transducers were attached to the paper, sending real-time tactile interpretations of the audio from the stethoscopes throughout its surfaces. The public was invited to touch, embrace, and be enveloped by the architectural folds of the sculpture as it evolved in concert with the intimate performance and sonic-scape.

In *Behind Your Eyes, Between Your Ears* [Item 61; 2016], Knut used alpha brain wave rhythms to control an interactive soundscape and project visuals that traced the dynamics of attention as the participant moved between thinking and being. Participating visitors wore a wireless brain wave sensor and focused their attention on unfolding a delicate electronic soundscape in which different layers of sound were revealed according to the intensity and duration of their alpha brain wave patterns. Abstract geometric visualizations of the brain wave activity then were projected onto the audience.

Pearlman's 2016 installation *Noor: A Brain Opera* [Item 64; 2016] was a 360-degree immersive EEG-driven performance. An EEG wireless headset triggered video, a sonic environment, and a libretto through brain waves and interaction with the audience. Naccarato's *Tangent* [Item 66; 2017] was presented as a dance theatre in which dancers performed behind the audience, and the rhythmic section of the music was provoked by the heartbeat of the dancers. *Harmonic Dissonance* [Item 67; 2018] was an immersive experience composed by Oostrik as an ever-evolving network based on physical, physiological, and brain group synchrony on computer-mediated social networks feeding back audio content to a 4.1 channel speaker setup.

Donnarumma presented *Alia: Zu tai* [Item 68; 2018] as a piece that combined dance theatre and biophysical multichannel music diffusion with AI robotics, as well as *Eingeweide* [Item 69; 2018] as a dance theatre piece in which sounds from the performers' muscular activity were amplified and transformed by AI algorithms into an immersive auditive experience. Finally, the piece *Vrengt* [Item 70; 2019], developed by Erdem, was based on EMG-shared instruments for music–dance performance, with a particular focus on sonic microinteraction.

TOWARD AN EMBODIED CONTROL STRUCTURE IN IMSs: FUTURE CHALLENGES

Historically, the notion of the interface has evolved significantly with the emergence of HCI studies and the rapid development of more complex black-boxed computing apparatuses that require comprehensible mediators between humans and machines. Biosensing control structures can be envisioned and framed as central nodes for new forms of communication or "dialogues" within an artistic perspective between the humans' bodies and brains and the machines. The assemblages of bodies, brains, and media conjure up new enactments for synchronicity, communication, wholeness, control, augmentation, and awareness that impact the general understanding of these intersections. Embodying one or more biosensing applications as a structural element of the artwork facilitates the integration of new media with music and composition, cinema, and performance arts to generate experiences that can enable a sense of magic within and inspire the audience.

Biosignal-driven IMSs serve as catalysts for potentially new musical expressions, body−instrument relations, sound in space technology, and performer−audience relationships of contemporary musicking in a network of reciprocal relationships. Personalizing technology through biosensing approaches can benefit musical studies, in that music presents a unique and highly intensive performance form (i.e., in terms of numbers of parameters, bodily training, timeliness, and embodiment). IMSs are cultural artifacts that are fluid and dynamic—never resting and continually opening up for new definitions and usages.

In this context, we discuss future challenges at the intersection of biosensing technology and IMSs. We envision several guidelines for future work based on the historical perspectives presented in earlier in this paper. Moreover, a need exists for a transdisciplinary approach toward art and technology to envision the future of biosignal-driven IMSs.

In Figure 6, we present our proposal for a biosignal-driven IMS roadmap for the next 5 years. The light gray outer blocks represent the foundational conditions guiding the appropriation of biosensors as control structures in IMSs, both in technological and artistic perspectives: interconnections, sensor technology, industrial standards, appropriation, control structures, and interaction. The inner gray blocks represent the foundational blocks' design and implementation in terms of technological and manufacturing developments. These biosensor advances encompass new materials engineering, such as electronic textiles (eTextiles); miniature electronics, such as those embedded in eTextiles; computing and communications that promote or facilitate interaction among several systems; systems engineering; and industrial design in developing the biosensing technologies. On the IMS side, the criteria are integration, efficiency and efficacy, information retrieval, open access, and musical practices. The left panels—materials and manufacturing methods—and the right panels—biosensing technologies and musical creativity—represent key roles in cementing the foundational blocks together and making biosignal-driven IMSs a physical manifestation. The interdependence across blocks can be understood as a techno-artistic ecosystem. The several blocks that compose the ecosystem are interdependent and ultimately influence future biosignal-driven IMS developments. From all standards presented above, we highlight three key ones that can inspire future applications of biosensor-driven IMS: integration, information retrieval, and accessibility of open-access hardware and software.

Concerning integration, the already existing low-cost biosensing wearable devices intertwine natural and artificial realities in pervasive and unobtrusive fashions. Hardware miniaturization, increasing processing power, and enhanced digital signal processing tools have expanded the depth of environmental awareness and biosensing across the multiple layers of human and machine communication. Biosensing is a particular signal manifestation at the front of the most exciting breakthroughs in this area of knowledge. Wireless biosensor textile integration can provide the ability to explore the design space and interactions this technology holds. Seamless integration with textiles can foster the creation of tools for techno-fluent artistic practices and advance transparent and personalized channels for the intercommunication of human activity within a broader context of an IMS. Interaction through an interconnected musical

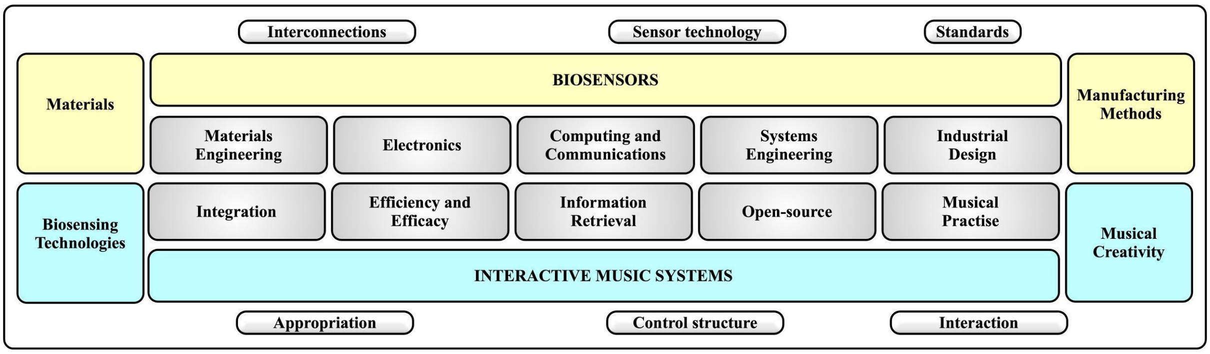

Figure 6. A roadmap for a transdisciplinary approach for biosensing technologies within IMSs, adapted from S. Park, Chung, & Jayaraman (2014). The light gray rounded blocks at the top and bottom represent the foundations that guide appropriation of biosensors as control structures in IMSs. The dark gray boxes provide criteria that affect the foundational blocks' design and implementation. The yellow blocks represent continuous technological developments concerning novel materials and manufacturing methods and the blue blocks present key roles in cementing methods when creating IMSs such as new forms of appropriation of biosensing devices for musical creativity.

instrument can foster ecosystems of interoperable musical devices and connect musicians and audiences, musician and musician, and audience and audience interactions. Beyond integration in textiles, biosensors could be placed on objects and in the environment, such as adding sensing capabilities to everyday life artifacts, thereby converting them into musical interfaces.

Concerning information retrieval, critical work involving congruent mapping between the categorical audio feature and context-mapping remains to be done. The integration of biosensing technologies as control structures in IMSs can be seen as a possible control structure for recalibrating music and sound in various contexts. Possible scenarios for augmenting biosensing technologies include health and well-being, video game soundtracking, and perceptual evaluation of auditory stimulus (e.g., noise annoyance, concentration and attention, relaxation, and mindfulness). Biosensor-driven IMSs can transform emotions into music and may help people recognize and understand their feelings and actions and those of other people. IMSs open the possibility of leveraging music—something HCI researchers seldom focus on—as one innovative way of expressing emotions to facilitate social interactions and augment performance.

Recent studies on brain-to-brain interfaces (BBI) were conducted on collaborative problem solving (Jiang et al., 2019). BBIs allow for technology-mediated direct communication between two brains without involving the peripheral nervous system. They consist of two components: an EEG that detects neural signals from one brain and translates them into computer commands and a computer–brain interface (CBI) that delivers computer commands to another brain. By combining EEG and magnetic stimulation, future IMSs could embed BBI features open to control by two humans telekinetically, thus promoting cooperation to achieve a desired musical goal. For example, a nonverbal musical instruction can be packed by a sender's brain to a receiver brain that would execute the desired motor response for performing the corresponding musical gesture. In societal terms, BBIs can be assembled as a sizable cloud-based network of individuals, both performers and audiences, who cooperate in unfolding an interactive musical piece. Other applications of BBIs include game music, sound enhancement, and user-state monitoring by sonification means.

In the ever-growing field of biosensing devices, we highlight the emergence of open-source brain–computer interfaces as the primary element of disruptive change in the significant adoption of the signals by a broader community of artists, most notably for interactive creations. Such devices include the Open-BCI (Durka et al., 2012) and the highly powerful, small, and low-cost biosensing toolkits BITalino (Da Silva et al., 2014). The convergence toward off-the-shelf technological solutions for biosensing is essential in enabling more comprehensive access and more successful practices with biosignals as control structures in IMSs. They ultimately could be embraced by a community of techno-fluent artists to be rooted in the artistic approach rather than the engineering focus. In this context, novel hardware devices and related software can promote more ready-to-use frameworks for interactive artists in extracting multidegrees of information, from continuous physical properties to high-level semantic information from the vast array of existing biosignals. Furthermore, low-cost, portable and ready-to-use devices can enlarge the scope of the biosensing spectrum in artistic applications toward more extensive audience participation within IMSs, thus engaging social experiences through a collective body.

CONCLUSIONS

Several taxonomies have been proposed in prior research for the emerging practice of bionsensor-driven IMSs. These proposals have focused on either the potential interactions with IMSs (Drummond, 2009; Ortiz et al., 2015; Prpa & Pasquier, 2019) or the characterization of biosignal data sources in HCI studies (da Silva, 2017). However, the interplay between the above in bionsensor-driven IMSs taxonomies is lacking in the literature, namely the emerging interaction of a musical system with the HCI affordances of the biosignal. To this end, we proposed a novel taxonomy for biosensor-driven IMSs that integrates both functional and empirical categories and allows their interrelated analysis. With our taxonomy, we offer IMS musicians a blueprint for mapping strategies in a more informed way and the ability to better predict their designs.

The novelty of our taxonomy relies on providing a viable framework for both analyzing and designing IMSs. A description of the biosensing system in terms of HCI and signal processing intertwined with a description of potential musical interactions fosters a better understanding of biosensing as a control structure in IMSs. We applied the proposed taxonomy to a curated catalog of 70 biosensor-driven IMSs spanning the 1965 biosensor-driven IMS by Alvin Lucier's *Music for a Solo Performer* until 2019. Each catalog entry was categorized according to the functional and empirical dimensions of our taxonomy, from which we extrapolated representative historical trends to critically verify our working hypothesis that biosensing in IMSs is expanding the array of control structures within IMSs.

We computed global statistics from the catalog data to extrapolate representative historical trends on three dimensions: type of sensor, response type, and performative affordances. The results revealed an extensive appropriation of EEG as a control structure in IMSs, although more recently other sensors have been appropriated, such as the case of the EMG. IMS musicians tend to seek a generative response in their systems. However, we identified the rise of transformative types of response possibly as a natural outgrowth of the increasing sophistication of algorithms for live sound processing, which in turn offer almost unlimited possibilities to design, create, and mix sounds in real-time. Finally, the performative affordances of analyzed IMSs historically denote higher prevalence of single performers. However, a growing trend reflects multiperformer with multisystems IMSs. We believe the advancements in interconnectivity and bandwidth velocity have fueled this recent trend.

Furthermore, the results showed three representative historical trends across all examined dimensions denoted as first practices (1965–1985), modern practices (1985–2005), and contemporary practices (2005–2019). The first historical practices involved a small group of early adopters of biosignal-driven IMSs, explained by the novelty of biosensing as a means of control and interaction within IMSs. The modern practices were marked by a decrease in the use of biosensors during the late 1980s and the resurgence of the practices in the 1990s. Finally, the contemporary practices encompass a larger set of biosensors at the disposal of the musician. The healthy growth in the availability of open-source devices, especially from the 2000s, allows for the artistic exploration of biosignals by a larger community of musicians.

Based on the recent trend observed in the collected data, we discussed the impact of smart and wearable biosensing technologies and the future challenges for their continuous appropriation as embodied control in IMSs. Technological developments such as new textiles with electronics embedded, miniaturization and computation power of novel devices accompanies the evolution of interactive systems, namely IMSs. New perspectives emerge from this dialogue, from designing IMSs with higher levels of understanding, such as emotion recognition, to distributed systems that communicate with each other, fostering collaborative, interactive musical compositions.

A possible limitation of our current analysis is its short-temporal span. The need for future reassessments of the historical periods is instrumental. As verified in other phenomena domains (Mollick, 2006), the fast pace at which technology evolves calls for constant revisions of the inner temporal trends. A future perspective may consider the three identified historical periods as belonging to a single phase, as their changes may become irrelevant in comparison with possible future endeavors of biosignal-driven IMSs.

Although advancing the connection and critical relation between empirical and functional dimensions of biosensor-driven IMSs and despite the statistical evidence supporting our findings, our study does not consider some inner mapping practices emerging in this context: of note, the impact of current machine learning and artificial intelligence algorithms for decoding and mapping biosignals to musical parameters of IMSs. Therefore, in future, such techniques should be considered as possible extensions of the taxonomy. Currently, the lack of a representative number of IMS is still scarce.

IMPLICATIONS FOR THEORY AND APPLICATION

The implications of our findings impact both future knowledge about and implementations of IMSs. By integrating functional and empirical dimensions, our proposed taxonomy permits the review of IMSs in a more integrated way. Supported by our taxonomy, IMS musicians can relate the sonic feedback with a description of biosignals in HCI. And with ongoing technological advances, the future applications of and research into IMS can open innovative practices and performances.

Another implication of our study is to provide critical analysis of historical trends of appropriation of biosignals as a control structure allowing practitioners and researchers to have a sharper picture of the historical developments of biosensing driven IMSs. From this foundation, further refinement in the taxonomy can allow the flexibility and dynamism necessary for ongoing research and practical advances in music performance.

ENDNOTE

1. Devices and sensors are equally considered in the obtrusiveness dimension, as they both can be worn and impose constraints to the physical experience of the user.

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