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Live Biofeedback as a User Interface Design Element: A Review of the Literature

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Abstract:

With the advances in sensor technology and real-time processing of neurophysiological data, a growing body of academic literature has begun to explore how live biofeedback can be integrated into information systems for everyday use. While researchers have traditionally studied live biofeedback in the clinical domain, the proliferation of affordable mobile sensor technology enables researchers and practitioners to consider live biofeedback as a user interface element in contexts such as decision support, education, and gaming. In order to establish the current state of research on live biofeedback, we conducted a literature review on studies that examine self and foreign live biofeedback based on neurophysiological data for healthy subjects in an information systems context. By integrating a body of highly fragmented work from computer science, engineering and technology, information systems, medical science, and psychology, this paper synthesizes results from existing research, identifies knowledge gaps, and suggests directions for future research. In this vein, this review can serve as a reference guide for researchers and practitioners on how to integrate self and foreign live biofeedback into information systems for everyday use.

Keywords: Human-computer Interaction, Literature Review, Live Biofeedback, NeuroIS, Transmission Model.

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1 Introduction

In recent years, the neuro-information systems (neuroIS) interdisciplinary research discipline (Riedl et al., 2010) has contributed to explaining users' cognitive and affective processes when interacting with information technology (IT). In summarizing ten key contributions that neuroIS has made to information systems research and practice, Riedl and Léger (2016) note that biofeedback systems, as a specific category of neuro-adaptive information systems, constitute one such contribution; that is, "systems that recognize the physiological state of the user and that adapt, based on that information, in real-time" (Riedl, Davis, & Hevner, 2014, p. i). Neurophysiological measurements provide users with indicators that can improve their perception of physiological activities and, thus, support emotion regulation and facilitate behavior change (Astor, Adam, Jerčić, Schaaff, & Weinhardt, 2013; Hariharan et al., 2017; Riedl & Léger, 2016). Live biofeedback systems provide users with real-time feedback about their own (self live biofeedback) or another person's (foreign live biofeedback) current physiological state—information that users of live biofeedback technology may have limited access to otherwise (Allanson & Fairclough, 2004; Astor et al., 2013). So far, researchers have studied live biofeedback primarily in the clinical domain, such as for mental health disorders (Monastra, Monastra, & George, 2002; Zucker, Samuelson, Muench, Greenberg, & Gevirtz, 2009)[1]. But since the proliferation of affordable mobile sensor technology has made non-health-related innovative applications of live biofeedback technologically and economically feasible (Al Osman, Eid, & El Saddik, 2013; Al Osman, Dong, & El Saddik, 2016), researchers have begun to employ live biofeedback as a user interface (UI) design element in application domains such as education and gaming to enhance, for instance, stress management and user experience.

Generally speaking, one can integrate the concept of live biofeedback into existing and emerging IT artifacts in two different ways. First, one can process biosignals in real time to design standalone live biofeedback systems that complement IT systems. For instance, Djajadiningrat, Geurts, Munniksma, Christiaansen, and De Bont (2009) developed EmoBowl, a system for financial traders that dynamically changes ambient light based on users' physiology in order to warn them during states of high emotional arousal. Hence, a standalone live biofeedback system that supports users in making financial decisions complements the financial trading IT artifact. Similarly, Astor et al. (2013) designed a standalone serious game-based live biofeedback system that allows users to train emotion regulation capabilities. Hence, instead of directly integrating biosignals into the actual trading interface, the standalone live biofeedback system enables users to develop skills (e.g., stress management) that they can then use in interacting with other IT systems (e.g., financial trading). Second, one can directly integrate live biofeedback as a built-in function into an IT artifact that the user uses for their primary task. In this regard, computer games represent a common application domain: researchers have used biosignals to improve user experience by dynamically adapting game elements (e.g., Nacke, Kalyn, Lough, & Mandryk, 2011; Reitz, Stockhausen, & Krömker, 2012).

In order to establish the current state of research on live biofeedback in an information systems context, we conducted a systematic literature review. We follow Webster and Watson's (2002) approach and examine studies that 1) investigate live biofeedback based on peripheral nervous system activity, 2) are situated in non-clinical domains with healthy subjects, and 3) include qualitative and/or quantitative evaluation with users. In our search, which we conducted in the Google Scholar database, we focused on keywords likely to occur in live biofeedback studies. Specifically, we searched for: "'realtime' OR 'real time' OR 'real-time' OR 'live' AND 'biofeedback'". Subsequently, we conducted a forward and backward search. As Figure 1 shows, the number of publications on live biofeedback has increased noticeably during the last 15 years. Overall, we identified 76 relevant papers published between 1977 and 2016 that cover self live biofeedback or foreign live biofeedback in the application domains of architecture, art, economic decision making, education, games, and wellbeing (see the Appendix for a detailed overview). In terms of research disciplines, the majority of studies came from computer science (27 studies on self live biofeedback, 20 studies on foreign live biofeedback)[2] followed by psychology (13+1), information systems (7+0), medical science (5+0), and engineering and technology (3+0).

[1] For a review of clinical biofeedback, see Futterman and Shapiro (1986) and Schoenberg and David (2014).

[2] Abbreviated in the following way: (number of papers on self live biofeedback + number of papers on foreign live biofeedback). We list all publications that used foreign live biofeedback in any way in Table A2 because they focused primarily on it even though some of these studies also include self live biofeedback. Due to the breadth of the search, a categorization solely according to the ABS ranking is insufficient. Hence, we additionally used the SCImago Journal and Country Rank (www.scimagojr.com/) to classify outlets into the five above-mentioned subject areas.

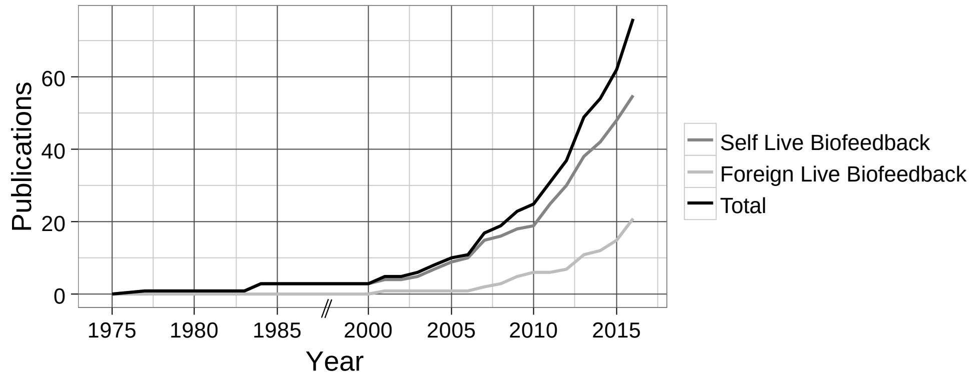

Figure 1. Number of Publications on Self Live Biofeedback and Foreign Live Biofeedback over Time

This paper makes four core contributions to information systems research and practice. First, based on Shannon and Weaver's (1949) transmission model of communication, we introduce a framework for live biofeedback research in information systems that clarifies the relationship between feedback sender and receiver and provides a frame of reference for investigating live biofeedback as a user interface element. Second, we synthesize current knowledge on self and foreign live biofeedback in computer science, engineering and technology, information systems, medical science, and psychology and outline key theories and the constructs they affect. Third, we review the various measurement tools that researchers have employed to compute live biofeedback and the different user interface elements they have used to convey a feedback response to the user. Fourth, we identify knowledge gaps in research on live biofeedback and develop suggestions for future research to fill these gaps.

2 An Integrative Framework for Live Biofeedback

2.1 Integrative Framework

In order to synthesize the results of the reviewed studies, we developed an integrative framework to conceptualize the components of live biofeedback systems (see Figure 2). This integrative framework for live biofeedback is based on Shannon and Weaver's (1949) transmission model of communication, which describes the communication process of information from a source to a destination on a conceptual level. Our model transfers the components of the transmission model of communication to the live biofeedback research domain in order to provide an intuitive illustration and shared frame of reference of the transmission processes between feedback source and feedback destination.

Similar to the transmission model of communication, the integrative framework for live biofeedback comprises four main components: 1) source, 2) transmitter, 3) receiver, and 4) destination. In a live biofeedback context, the source refers to a person's physiological activity and the biosignals obtained from this current state (e.g., electrical activity of the heart). The transmitter, a measurement tool, acquires the physiological activity by transforming this information into a signal (e.g., electrocardiography, ECG), extracts physiological features (e.g., heart rate, HR) and transmits the signal to the receiver. Receivers represent user interfaces, which manifest feedback to users by converting the received signal into a visual (e.g., a scale to indicate the level of HR), auditory (e.g., a tone to indicate the level of HR), or tactile (e.g., vibration) stimulus. Thus, the receiver transforms the signal into a message that it sends to the destination (i.e., the user). Users can process and interpret this message, which may cause them to change their perception, behavior, and regulation of their physiological activity. Thus, taken as a whole, the framework captures the communication process between the human body, the live biofeedback system, and the human mind (for a similar conceptualization, see Al Osman et al., 2014). In the Appendix, we map the reviewed studies to the proposed model and provide detailed information on the respective components in separate Venn diagrams (see Figure A1).

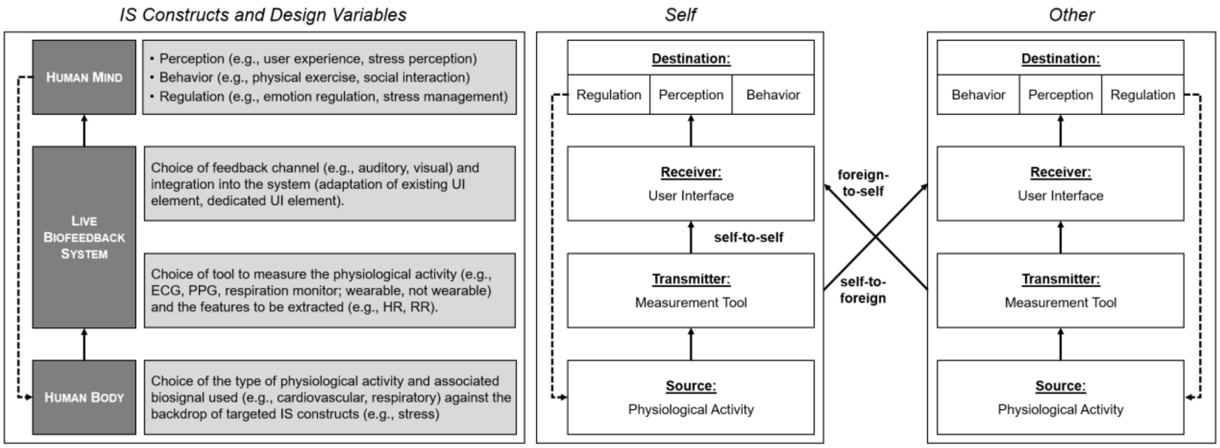

Figure 2. Integrative Framework for Live Biofeedback

The integrative framework builds on the widely employed definition of live biofeedback by the Association for Applied Psychophysiology and Biofeedback (AAPB), the Biofeedback Certification International Alliance (BCIA), and the International Society for Neurofeedback and Research (ISNR):

> *Biofeedback is a process that enables an individual to learn how to change physiological activity for the purposes of improving health and performance. Precise instruments measure physiological activity such as brainwaves, heart function, breathing, muscle activity, and skin temperature. These instruments rapidly and accurately "feed back" information to the user. The presentation of this information—often in conjunction with changes in thinking, emotions, and behavior—supports desired physiological changes. Over time, these changes can endure without continued use of an instrument.* (AAPB, 2011)

This definition and its many variations in related studies share the view that biofeedback comprises the measurement of physiological activities and the generation of a feedback response that addresses at least one of a person's five senses (auditory, gustatory, olfactory, tactile, and visual) in order to trigger a change in perception, behavior, and regulation of physiological activities (Al Osman et al., 2013; Hilborn, Cederholm, Eriksson, & Lindley, 2013; Riedl & Léger, 2016).

Conceptually, one can provide people with feedback on their own physiological activity or on others' physiological activity. Therefore, the framework comprises three scenarios in which transmission signals are sent from one person to the same person or to another person. In scenario one ("self-to-self"), a person receives a transmission signal based on their own physiological activity (e.g., Buttussi, Chittaro, Ranon, & Verona, 2007; Feijs, Kierkels, Van Schijndel, & Van Lieshout, 2013). In scenario two ("foreign-to-self"), a person (self) *receives* a transmission signal based on another person's (other) physiological activity (e.g., Al Mahmud et al., 2007; Curmi, Ferrario, Southern, & Whittle, 2013). In scenario three ("self-to-foreign"), a person (self) *knows* that someone else (other) receives their physiological activity as a transmission signal (e.g., Tan, Schöning, Luyten, & Coninx, 2014; Walmink, Wilde, & Mueller, 2013). One needs to distinguish between foreign-to-self and self-to-foreign signals because 1) subjects might not realize that their physiological activity is being recorded and 2) the provision of biofeedback might affect the users' perception, behavior, and regulation of physiological activities in different ways. We consider these three scenarios in mapping the reviewed studies to the integrative framework for live biofeedback in the Appendix (see Figure A1).

2.2 Source: Physiological Activity

Researchers often consider choosing what physiological activity to use as a source for a specific biofeedback system as one of the most difficult design decisions. They do so due to the complex relationship between a psychological phenomenon and physiological activity (e.g., cardiovascular activity as a proxy for stress), which strongly depends on the context (i.e., environmental influences) and can potentially overlap with other phenomena (Andreassi, 2000; Cacioppo, Tassinary, & Berntson, 2007). Overall, one can divide physiological activity into activity of the central nervous system, the peripheral nervous system, and the endocrine (hormone) system (Riedl et al., 2014; Riedl & Léger, 2016)[3]. In this review, we focus on activity of the peripheral nervous system (PNS) because its measurement interferes little with tasks, places few restrictions on user behavior, and can be applied “over longer periods in natural environments” (Riedl & Léger, 2016, p. 58)—important characteristics for live biofeedback systems. Moreover, consumer-grade mobile measurement devices for the PNS have become increasingly affordable and widely adopted.

The PNS comprises two subsystems: the somatic system and the autonomic nervous system. While the somatic system comprises motor nerves to voluntarily control muscle activation, the autonomic nervous system regulates and coordinates physiological processes generally outside of volitional control (Andreassi, 2000). Further, the autonomic nervous system itself has two branches: 1) the excitatory sympathetic nervous system that is related to increased physiological activation due to mobilized energy resources in emergency and stress situations (“fight or flight”) and 2) the inhibitory parasympathetic nervous system that is related to physiological deactivation or relaxation during the return to safer circumstances (“rest and digest”) (Andreassi, 2000). Both the somatic system and the autonomic system play an important role in live biofeedback research. The somatic system is mostly related to muscle activity-based feedback (e.g., frowning and smiling (Rani, Sarkar, & Liu, 2005) and body movement (Höysniemi, Aula, Auvinen, Hännikäinen, & Hämäläinen, 2004)). Users can use this type of biofeedback to, for example, control game mechanics (Nacke et al., 2011). In contrast, the autonomic nervous system is mostly related to feedback for physiological activation and deactivation (e.g., cardiovascular activity (Nenonen et al., 2007) and electrodermal activity (Cederholm, Hilborn, Lindley, Sennersten, & Eriksson, 2011)). Users can use this type of biofeedback to, for example, manages stress (Al Osman et al., 2013).

2.3 Transmitter: Measurement Tools

With respect to live biofeedback systems, we refer to transmitters as measurement tools that measure physiological activity in real time by converting it into an electric signal, extract features from this signal, and transmit these extracted signals to a receiver (i.e., self-to-self, foreign-to-self, and self-to-foreign in Figure 2). When choosing a measurement tool, one needs to consider the physiological activity one wants to measure and the features one wants to extract from this physiological activity. For instance, to acquire cardiovascular activity, one could use electrocardiography (ECG) and photoplethysmography (PPG). Based on the measured cardiovascular activity, one can derive physiological features such as heart rate, heart rate variability (HRV), or pulse transit time (PTT). One can acquire information on movement, for example, via electromyography (EMG), which measures fine muscle activity based on electrical potentials, or via video cameras, which can capture posture or overall body movement. Furthermore, one can extract physiological features such as skin conductance level (SCL) and skin conductance response (SCR) from measurements of electrodermal activity (EDA).

When choosing a measurement tool for a live biofeedback system, one needs to carefully evaluate its strengths and weaknesses in terms of costs, accessibility, degree of artificiality/intrusiveness, labor- and time-intensity of data processing, and measurement issues/susceptibility (Dimoka et al., 2012). For designers of live biofeedback systems that build on cardiovascular activity, for example, one would need to weigh the strengths (e.g., little impairment) and weaknesses (e.g., increased susceptibility through movement artifacts) of heart rate measurement through remote photoplethysmography (rPPG) against the strengths (e.g., high accuracy) and weaknesses (e.g., higher costs) of ECG (Rouast, Adam, Chiong, Cornforth, & Lux, 2016).

2.4 Receiver: Manifestations in the User Interface

We refer to live biofeedback manifestations as the way in which users receive feedback. Live biofeedback manifestations in user interfaces address at least one of the five human senses—sight (visual), hearing (auditory), touch (tactile), taste (gustatory), and smell (olfactory). Researchers commonly view vision as the dominant sensory modality in human perception (Shams & Beierholm, 2010) and, correspondingly, most often use visual elements/objects to provide live biofeedback. However, when designing a user interface, one should consider the appropriateness of a sense (or senses) to provide additional information in a specific situation. Furthermore, some live biofeedback systems combine several types of manifestations in their user interface (e.g., visual and acoustic) because research has shown that

[3] For a comprehensive overview of neuroIS methodology, tools, and measurements, we suggest readers read Dimoka et al. (2012), Riedl et al. (2014), and Riedl and Léger (2016).

addressing multiple senses improves and accelerates individuals' ability to detect, localize, and react to external stimulation (Stein & Meredith, 1993).

One can manifest feedback by adapting 1) an existing UI element, 2) a new, dedicated UI element, or 3) a combination of both. The first type of live biofeedback manifestation, which uses existing UI elements such as game mechanics (Nacke et al., 2011) or real-world objects in the workspace or household such as ambient light (Matthews et al., 2015; Snyder et al., 2015), commonly focuses on not disrupting the user's natural environment as much as possible. In contrast, the second type of manifestation employs dedicated elements and objects for feedback manifestation, such as a dedicated arousal meter integrated into the UI (Astor et al., 2013; Fernández, Augusto, Trombino, Seepold, & Madrid, 2013) and dedicated real-world objects such as a tangible avatar (Gervais, Gay, Lotte, & Hachet, 2016) or a butterfly bracelet (MacLean, Roseway, & Czerwinksi, 2013) to achieve a higher level of feedback salience, which comes at the cost of increased obtrusiveness. The third type of manifestation combines the first two approaches by integrating dedicated elements into existing elements in order to reduce the disturbance of the user's natural environment through additional dedicated feedback manifestations (e.g., Walmink et al. (2013) attach a display of the user's heart rate to a bicycle helmet). Overall, when choosing a manifestation for a user interface, one needs to consider the situation and social context. For instance, MacLean et al. (2013) observed that indiscrete feedback manifestations, such as their butterfly bracelet, can make users feel uncomfortable.

2.5 Destination: User Perception, Behavior, and Regulation of Physiology

Live biofeedback systems ideally cause a change in one or more focal constructs that pertain to users' perception, behavior, and/or regulation of physiological activity. Generally speaking, a "*construct* is a conceptual term used to describe a phenomenon of theoretical interest" (Edwards & Bagozzi, 2000, pp. 156-157, emphasis in original). Importantly, however, investigating such a phenomenon (e.g., stress) may require researchers to "consider multiple analytical levels in order to fully capture the phenomenon" (Riedl et al., 2014, p. x)—particularly for many live biofeedback applications that employ measurement tools to assess the physiological dimension of a phenomenon (e.g., physiological stress) to trigger a change in its perceptual dimension (e.g., perceived stress) (Chittaro & Sioni, 2014). Further, if designed accordingly, the live biofeedback system can trigger a change in user perception and, thus, support users in regulating their physiological activity (e.g., stress management), which, if effective, closes the feedback loop and results in changes in their physiology (Al Osman et al., 2013; Astor et al., 2013).

In this context, we need to highlight that live biofeedback systems address two different categories of focal constructs. The first category refers to constructs that are *directly* associated with physiological activity. In other words, a physiological dimension of the focal construct exists (e.g., arousal, stress). For this category of constructs, live biofeedback systems commonly focus on supporting users in developing interoceptive skills (i.e., skills to sense their own or another person's physiological activity) (Craig, 2003; Dunn et al., 2010), which can increase the coherence between the physiological dimension and the perceptual dimension of the construct (Bonanno & Keltner, 2004; Mauss, Levenson, McCarter, Wilhelm, & Gross, 2005). Further, strengthening interoceptive skills can help users change their behavior and regulate their physiological activity (Al Osman et al., 2013; Riedl & Léger, 2016). In particular, Green, Green, and Walters (1970) have postulated the body-mind loop, a psychophysiological principle that states that changes in people's mental-emotional state can affect their physiological activity and vice versa.

The second category refers to constructs that are *indirectly* associated with physiological activity. For instance, providing users with feedback on their own or others' physiology may improve their user experience or facilitate social interaction. In other words, providing users with live biofeedback influences the focal construct, but the measured physiological activity does not constitute a physiological dimension of the construct. For instance, several studies have examined how foreign live biofeedback may facilitate social situations and investigated whether one can use foreign live biofeedback to alter social situations (e.g., by using live biofeedback as a social cue) to increase social presence (Järvelä, Kätsyri, Ravaja, Chanel, & Henttonen, 2016), the enjoyment of a social activity (Stach et al., 2009), support social exertion experiences (Walmink et al., 2013), or reduce stress in a collaboration task (Tan et al., 2014).

2.6 The Interplay between the Components in the Framework

Due to the dynamic nature of live biofeedback systems, they involve continuous interplay between their key components (i.e., source, transmitter, receiver, and destination). With respect to transmitters and receivers, we can conceptualize three different pathways as the transmission signals self-to-self, foreign-to-self, and self-to-foreign indicate. From the perspective of a particular person, all three signals can be transmitted simultaneously. While self live biofeedback systems address the dynamic interplay of physiological activity, perception, and regulation *within a person* (self-to-self), foreign live biofeedback address the context of social interactions *between individuals*. Through foreign live biofeedback, a user receives feedback on another user's physiological activity (foreign-to-self), or a person knows that someone else receives their physiological activity as a transmission signal (self-to-foreign)[4]. Research has found foreign live biofeedback to be particularly useful in the context of easing social interactions, which the sending and receiving of social cues and the inferences drawn from these cues drive (Howell et al., 2016; Järvelä et al., 2016; Snyder et al., 2015).

Importantly, because live biofeedback systems provide information on physiological activity in real time, the change in user perception that the receiver component causes can, in turn, affect that same physiological activity. In fact, supporting users in regulating their physiological activity often represents a key aspect of such systems (e.g., emotion regulation, stress management). Based on this mutual dependence of physiological activity, measurement tool, user interface, and user perception (i.e., source, transmitter, receiver, and destination), one needs to attune all components to one another when designing a live biofeedback system. Because all of these components are at play simultaneously, each individual component is critical for the live biofeedback system as a whole to be effective. In Sections 3 to 8, we discuss each component in detail.

3 Physiological Activity

3.1 Overview of Physiological Activity Investigated in Live Biofeedback Literature

Altogether, we found that biofeedback studies diverge substantially with respect to the measured physiological activities. Most studies acquire cardiovascular activity (37+16)[5]. Many also measure electrodermal activity (20+7), body movement (15+3), and respiration (17+4). Few integrate eye activity (1+1) and body temperature (4+0) into live biofeedback applications. Most studies acquire only one physiological activity (35+13). However, several studies (20+8) assess multiple activities, of which five studies on self live biofeedback and one study on foreign live biofeedback measure more than three physiological activities simultaneously. More than half of all studies that measure multiple physiological activities acquire cardiovascular and electrodermal activity (12+4).

3.2 Interpretation of Physiological Activity

Recent research provides evidence that physiological activity relates to psychological constructs such as stress or fear (Cacioppo et al., 2007; Dimoka et al., 2012; Gregor, Lin, Gedeon, Riaz, & Zhu, 2014). However, the relation between physiological activity and psychological constructs is not always clear because research has shown that physiological activity is also associated with several sources of variance such as physical activity or environmental influences. Thus, Mauss and Robinson (2009), who investigated measures of emotion, found that no "gold standard" measure of psychological constructs exists. In order to deduce a meaningful assessment from physiological activity, such as determining arousal from phasic electrodermal activity (Boucsein, 2012), one needs to properly isolate the effect that the psychological construct and other sources (e.g., environmental temperature) cause (Bakker, Pechenizkiy, & Sidorova, 2011). Therefore, if one seeks to use a live biofeedback system to provide information about a psychological construct by using physiological activity as a proxy, one faces challenges in asserting the validity and reliability of the physiological signal as a proxy for the physiological dimension of that construct. However, some live biofeedback systems do not use physiological activity as a proxy but influence a psychological construct that indirectly influences the measured physiological activity. Studies with such systems use them to support social interactions between multiple individuals by, for instance, showing heart rate information to influence interpersonal engagement (e.g., Järvelä et al., 2016; Slovák, Janssen, & Fitzpatrick, 2012).

The studies we surveyed investigate a variety of relationships between physiological activities and user perception. Several studies use cardiovascular activity (Al Osman et al., 2013, 2016; Astor et al., 2013;

[4] A special case of foreign live biofeedback is group live biofeedback in which each group member receives feedback either individually or in an aggregate manner (e.g., a collective stress level) (Fernández et al., 2013).
[5] Abbreviated as before: number of papers on self live biofeedback + number of papers on foreign live biofeedback.

Feijs et al., 2013; Hilborn et al., 2013; Millings et al., 2015) or electrodermal activity to facilitate stress perception. With respect to serious and playful games, the studies integrate a wide variety of physiological activities such as cardiovascular activity, electrodermal activity, (electrical) muscle activity, body movements, eye activity, respiration, and body temperature into live biofeedback systems to increase excitement (Tennent et al., 2011), enjoyment (Nacke et al., 2011), fear (Ueoka & Ishigaki, 2015), satisfaction (Tennent et al., 2011) and (virtual) social competition (De Oliveira & Oliver, 2008). While most studies that focus on increasing the perception of social presence or social connectedness measure cardiovascular or electrodermal activity (Howell et al., 2016; Järvelä et al., 2016; Roseway, Lutchyn, Johns, Mynatt, & Czerwinski, 2015; Slovák et al., 2012; Walmink et al., 2013), some provide feedback based on a combination of several physiological activities (Curmi et al., 2013; Gervais et al., 2016).

3.3 Direct and Indirect Control of Physiological Activity

One can distinguish live biofeedback applications into two groups based on whether they measure physiological activity that can be *directly* or *indirectly* controlled (Nacke et al., 2011). The most commonly used measurement tools measure cardiovascular and electrodermal activity. In both cases, one can only indirectly control the underlying bodily functions because, for example, autonomous reactions trigger the electric activity of the heart muscle fibers, changes in blood flow, and alterations in skin conductance. Similarly, users cannot directly control their body temperature, which live biofeedback applications seldom use. Physiological activities with a higher degree of control include body movements (e.g., measured through electromyography (EMG), GPS, and video), eye activity (e.g., measured through electrooculography (EOG) or eye tracking), and respiration (e.g., measured with an optical sensor or a girth sensor). Hence, depending on the specific application scenario, researchers and practitioners might need to consider the required and also the possible level of control when choosing an appropriate biosignal for their live biofeedback application.

Some live biofeedback systems also focus on increasing how well users can control usually indirectly controlled body functions. For example, one early live biofeedback systems from Goldstein, Ross, and Brady (1977) provides information on cardiovascular activity in order to allow users to deliberately reduce their heart rate (see also Peira, Fredrikson, & Pourtois, 2014). Furthermore, Pastor, Menéndez, Sanz, and Abad (2008) provide users real-time feedback on their electrodermal activity in order to help them to reduce their skin conductance level. Thus, these systems support the voluntary regulation of physiological activities that the autonomic nervous system triggers (Xiong, He, Ji, & Wu, 2013).

In contrast, systems that build on physiological activity that users can more directly control commonly focus on supporting behavior change or facilitate system control. For example, some studies use respiration-based systems to foster meditative experiences (Vidyarthi, Riecke, & Gromala, 2012) or teach respiration-pacing techniques (Moraveji et al., 2011), and others use acceleration-based systems to support swimming (Li, Cai, Lee, & Lai, 2016) or rowing (McGregor, Buckeridge, Murphy, & Bull, 2016). Vieira, Baudry, and Botter (2016) use EMG-based live biofeedback to reduce calf muscle activation during standing, and several systems use voluntarily controlled physiological activity as user input for serious and playful games (Al Osman et al., 2016; Nacke et al., 2011; Tennent et al., 2011). Interestingly, we found that researchers have mainly used physiological activity that users can directly control in their self live biofeedback systems. With the exception of Moran, Jäger, Schnädelbach, and Glover's (2016) actuated environmment for supporting yoga breathing practices, all foreign live biofeedback systems use physiological activity that users cannot directly control. As for why, system designers might mainly use foreign live biofeedback systems to support social interaction and increase user experience, and, in order to do so, they chose to provide additional information that users have no access to otherwise.

4 Measurement Tools and Physiological Features

4.1 Overview

The transmitter component refers to the tools that one employs to measure the physiological activity (e.g., cardiovascular activity, electrodermal activity, respiratory activity) and extract features (e.g., heart rate, skin conductance level, respiratory rate) from it. We found that about two thirds of the studies that measure cardiovascular activity use ECG (25+11) and about one third use PPG (12+5). Interestingly, all five live biofeedback systems that provide information on a person's physiological activity to other users but not to the respective person (i.e., live biofeedback systems that transmit foreign-to-self and self-to-foreign but not self-to-self signals) measure cardiovascular activity with either ECG or PPG (Al Mahmud et al., 2007; Curmi et al., 2013; Mueller & Walmink, 2013; Tan et al., 2014; Walmink et al., 2013). After tools that measure cardiovascular activity, studies most commonly used surface electrodes to measure EDA (20+7) and chest straps to measure respiration (17+4). Studies measure body movement with EMG (7+0), accelerometers (5+2), GPS (1+1), and video (2+0). Four studies (4+0) use thermometers to measure body temperature and two studies capture eye activity (one with eye trackers (1+0) and one with EOG (0+1))[6].

More than half of the 76 reviewed studies (48 studies) investigate live biofeedback systems that provide feedback based on only one measurement tool (also called unimodal live biofeedback systems). Of the remaining studies, 15 systems combine two, seven combine three, and six combine even more measurement tools (called multimodal live biofeedback systems). Just under half (12 of 28) of these systems combine ECG and EDA measurements. Chittaro and Sioni (2014) compare unimodal and multimodal live biofeedback and suggest that "a single-sensor approach is more practical and less costly, but the use of multiple physiological sensors may improve the accuracy" (p. 664). However, their study did not bear out this thought; users perceived the unimodal system as more accurate than the placebo condition, while the multimodal system scored even lower than placebo feedback.

4.2 Measurement of Cardiovascular Activity

The majority of studies, especially those that address constructs related to emotional arousal and social interaction, employ ECG and PPG to determine the number of heart beats in a given time frame or the intervals between subsequent heart beats to extract heart rate and HRV. Studies commonly sample ECG and PPG with at least 250 Hz (see e.g., Al Osman et al., 2013; Munafò, Patron, & Palomba, 2016; Xiong et al., 2013). For preprocessing, most studies apply a series of filters such as high-pass filters (Al Mahmud et al., 2007; Järvelä et al., 2016), low-pass filters (Al Mahmud et al., 2007; Yu et al., 2016), band-pass filters (Gervais et al., 2016; Liu, Agrawal, Sarker, & Chen, 2009), or the Butterworth filter (Xiong et al., 2013) to remove implausible frequencies from the signal that movement or signal noise artifacts cause before extracting the heart rate and related features from the ECG signal. Thereby, they rely on existing open source or proprietary algorithms (see e.g., Hamilton, 2002; Pan & Tompkins, 1985; Sasikala & Wahidabanu, 2010). One might explain the wide use of heart rate measurements by the notion that most users have an intuitive understanding of this parameter, which enables them to interpret it as a source of "objective *information* about one's own or someone else's internal state" and a "direct *connection* to the other" (Slovák et al., 2012, p. 863, emphasis in original). Psychophysiological research has used changes in heart rate as a proxy for increased attention, emotional arousal, and cognitive effort (Cacioppo et al., 2007), and, in the context of foreign live biofeedback systems, heart rate serves as an indicator for social presence (Järvelä et al., 2016; Slovák et al., 2012), exertion (Mueller et al., 2010; Mueller & Walmink, 2013; Walmink et al., 2013), and emotional arousal (Astor et al., 2013; Hilborn et al., 2013; Jercic et al., 2012).

Studies commonly interpret HRV as an indicator for the overall activity and interplay of the sympathetic and the parasympathetic branches of the ANS (Al Osman et al., 2013; Xiong et al., 2013). By measuring, for instance, the variation of the time between subsequent heart beats, studies use HRV as a measure for autonomic balance (Hicks, Hunt, Alvut, Hope, & Sugarman, 2014; Rijken et al., 2016; Xiong et al., 2013), stress (Al Osman et al., 2013, 2016; Millings et al., 2015; Rijken et al., 2016), anxiety (Liu et al., 2009), and emotional valence (Roseway et al., 2015). With the exception of three studies that use PPG (Ebben, Kurbatov, & Pollak, 2009; Sakakibara, Hayano, Oikawa, Katsamanis, & Lehrer, 2013; Yu et al., 2016), studies use ECG as a tool to derive HRV from cardiovascular activity. Due to the requirement for real-time updates in most live biofeedback systems, only 13 (11+2) out of 53 studies that measure cardiovascular activity employ HRV measures, which is likely because HRV measures need to be calculated using time windows between 16 detected heart beats (about 10-20 seconds, e.g., Yu et al., 2016) to five minutes (Roseway et al., 2015). Most of the reviewed studies use time windows of three to five minutes for HRV. In the time domain, the employed HRV features include standard deviation of inter-beat intervals (SDNN; Al Osman et al., 2013; Rani et al., 2005; Xiong et al., 2013; Yu et al., 2016), standard deviation of differences between adjacent RR intervals (SDSD; Xiong et al., 2013), root mean square of successive

[6] While EEG-based live biofeedback falls outside the study's scope, we note that four studies that employ the measurements that we mention above additionally include EEG measurements, and, thus, we include them in this review (see Tables A1 and A2 in Appendix A). Similarly, eye tracking and facial expression recognition are important areas to determine a user's cognitive and affective state (e.g., driver fatigue detection (Horng, Chen, Chang, & Fan, 2004) and area of interest capture (Léger et al., 2014)). However, studies that focus mostly on eye tracking and facial expression recognition fall outside the study's scope.

difference (rMSSD; Roseway et al., 2015; Xiong et al., 2013), and number or percentage of successive NN intervals that vary by more than 20 or 50 milliseconds (NN20, NN50 or pNN20, pNN50; Xiong et al., 2013). In the frequency domain, the employed HRV features include high frequency (HF) (Al Osman et al., 2013, 2016; Millings et al., 2015; Rijken et al., 2016; Xiong et al., 2013), low frequency (LF) Al Osman et al., 2013, 2016; Hicks et al., 2014; Millings et al., 2015; Rijken et al., 2016; Xiong et al., 2013), and very low frequency (VLF) (Rijken et al., 2016; Xiong et al., 2013) components of the HR signal. Interestingly, only two foreign live biofeedback studies employ HRV measures, and both build on time-domain features (i.e., SDNN, rMSSD (Roseway et al., 2015; Yu et al., 2016). One might explain this finding by the notion that HRV is even more difficult to interpret in an interpersonal setting.

4.3 Measurement of Electrodermal Activity

Activity of the eccrine sweat glands results in variations of the electrical characteristics of the skin (also known as EDA). Studies usually measure EDA with two electrodes attached to a user's palm or fingers (Boucsein, 2012; Munafò et al., 2016; Perera, Perera, Rathnarajah, & Ekanayake, 2016). However, several live biofeedback systems use less-obtrusive measurement tools such as the "Personal Input Pod" that users can hold in between two fingers (Dillon, 2016; Matthews et al., 2015), a wristband (Roseway et al., 2015), or a glove (Gervais et al., 2016). All reviewed studies measure EDA by applying a constant voltage, which implies that they all record EDA in terms of skin conductance (SC) (Boucsein, 2012). The studies extract tonic and phasic features from the signal. If tonic phenomena are of interest (i.e., phenomena during non-stimulus-specific periods), the studies measure the skin conductance level (SCL) (Feijs et al., 2013; Hicks et al., 2014; Pastor et al., 2008). If phasic phenomena are of interest (i.e., phenomena that occur as a response to specific stimuli), the studies measure the skin conductance response (SCR) (Dillon et al., 2016; MacLean et al., 2013; Rani et al., 2005; Tan et al., 2014). Studies that employ EDA measurements usually analyze the slope or the amplitude of the measured SC signal (Chittaro & Sioni, 2014; Dillon et al., 2016; Hicks et al., 2014). Perera et al. (2016) used information on the area under the curve. Sample rates vary from 5 Hz (Perera et al., 2016) to 2048 Hz (Chittaro & Sioni, 2014). In order to remove artifacts due to, for example, poor contact between sensors and skin or signal disturbance (Perera et al., 2016), studies frequently apply filters such as low-pass filters (Howell et al., 2016) and band-pass filters (MacLean et al., 2013). Furthermore, the studies often smooth the acquired signals by applying moving average filters (Matthews et al., 2015; Perera et al., 2016). Because EDA is innervated exclusively by the somatic nervous system (Boucsein, 2012), many live biofeedback systems measure this activity as a proxy for stress (Chittaro & Sioni, 2014; Dillon et al., 2016; MacLean et al., 2013; Matthews et al., 2015; Perera et al., 2016). Furthermore, they measure EDA to facilitate psychophysiological self-regulation when individuals, for instance, meditate, engage in mindfulness practices, self-hypnotize (Hicks et al., 2014), and reflect on their emotional states (Gervais et al., 2016; Howell et al., 2016) to increase their wellbeing (Bouchard et al., 2012; Dillon et al., 2016; Pastor et al., 2008) and support social interaction (Gervais et al., 2016; Howell et al., 2016; Picard & Scheirer, 2001; Roseway et al., 2015).

4.4 Measurement of Body Movement

Studies use sensors such as surface EMG, accelerometers, GPS, video recordings, and pedometers to measure body movement in live biofeedback systems. They often use EMG to detect facial movements, especially smiling and frowning, based on muscle activity (Chittaro & Sioni, 2014; Liu et al., 2009; Rani et al., 2005). They frequently measure overall body motion with tri-axial accelerometers (Buttussi et al., 2007; Horta, Lopes, Rodrigues, & Misra, 2013; Li et al., 2016; McGregor et al., 2016) that are, for instance, integrated in a chest strap (Buttussi et al., 2007). One study uses consumer-grade video cameras to detect a user's overall body movements (Höysniemi et al., 2004). With respect to applied sample rates, we found that studies sample EMG signals at 2048 Hz (Chittaro & Sioni, 2014; Vieira et al., 2016) and accelerometers at 10 Hz (Li et al., 2016) to 100 Hz (Al Osman et al., 2016) and that studies acquire GPS signals approximately every four seconds (Curmi, Ferrario, & Whittle, 2017). After acquiring an EMG signal, Vieira et al. (2016) amplify the signal by factor 1000 to 5000 to maximize the signal to noise ratio. Furthermore, studies filter EMG signals by, for example, applying a low-pass filter (Liu et al., 2009), band-pass filter (Chittaro & Sioni, 2014), and Butterworth filter (Vieira et al., 2016). Features that studies extract from EMG include mean, slope, standard deviation, mean frequency, and median frequency (Liu et al., 2009; Rani et al., 2005; Vieira et al., 2016). For deriving features in the frequency domain (e.g., mean frequency), studies apply the fast Fourier transformation (Liu et al., 2009). While studies use EMG-based systems to detect stress (Al Osman et al., 2016; Chittaro & Sioni, 2014;

Reynolds, 1984) and anxiety (Liu et al., 2009; Rani et al., 2005), they use live biofeedback systems that incorporate accelerometers to help users evaluate and optimize their posture and exercise performance (Buttussi et al., 2007; Li et al., 2016; McGregor et al., 2016). Furthermore, because accelerometers measure voluntary body movements, studies use their measurements as user input for gameplay control to enhance user experience (Buttussi et al., 2007; Nacke et al., 2011). Studies use video cameras to detect a speaker's smiling and eye contact with the audience to train people in public speaking (Chollet, Wörtwein, Morency, Shapiro, & Scherer, 2015) and to detect people's movements in order to reach an optimal exercise level (Höysniemi et al., 2004). The two studies that evaluate live biofeedback systems with GPS use these measurements as additional sensors to ECG to detect the user's location (Curmi et al., 2013; Davis et al., 2005). Finally, Magielse and Markopoulos (2009) integrate step-count information into a game to enhance social interaction.

4.5 Measurement of Respiratory Activity

Studies commonly measure respiratory activity with chest belts that track chest expansion/contraction (Moran et al., 2016; Schnädelbach, Glover, & Irune, 2010; Schnädelbach, Irune, Kirk, Glover, & Brundell, 2012; Vidyarthi et al., 2012). Munafò et al. (2016) even use two belts, one worn around the thorax and the other around the abdomen, to record respiratory activity. Belts used in live biofeedback systems include, for instance, the Zephyr BioHarness Belt (Al Osman et al., 2013, 2016; Al Rihawi et al., 2014) or the Plux Respiration sensor (Muñoz et al., 2016). Sampling frequencies for acquiring respiratory activity vary from 20 Hz (Tennent et al., 2011) to 25 Hz (Al Osman et al., 2013, 2016; Xiong et al., 2013). Studies use a low pass filter (Al Osman et al., 2016), band pass filter (Muñoz et al., 2016), and Butterworth filter (Xiong et al., 2013) to remove the baseline drift and any inconsistent measurements and smooth out the signal. Commonly extracted features include respiratory rate (Al Osman et al., 2013, 2016; Al Rihawi, Ahmed, & Gutierrez-Osuna, 2014; Meier & Welch, 2016; Muñoz et al., 2016; Schnädelbach et al., 2012; Tan et al., 2014), amplitude (Schnädelbach et al., 2012), volume (Nacke et al., 2011; Vidyarthi et al., 2012), abdominal respiration (Munafò et al., 2016), thoracic/abdominal ratio (Vidyarthi et al., 2012), and, when the study measures cardiovascular activity as well, respiratory sinus arrhythmia (Munafò et al., 2016). Most studies use respiration-based live biofeedback systems to manage stress (Al Osman et al., 2013, 2016; Al Rihawi et al., 2014; Meier & Welch, 2016; Munafò et al., 2016) through, for instance, paced breathing (Meier & Welch, 2016; Morie et al., 2011; Xiong et al., 2013), facilitating autonomic regulation (Munafò et al., 2016), and supporting meditation (Vidyarthi et al., 2012), yoga (Moran et al., 2016), or resilience training (Morie, Chance, & Buckwalter, 2011). Because people can voluntarily control their breathing, studies also use it to control game mechanics (Marshall et al., 2011; Nacke et al., 2011; Tennent et al., 2011).

4.6 Measurements with Mobile Sensors

Studies frequently use mobile sensor technology to use live biofeedback in more natural settings. Portable and wearable sensors offer greater mobility, lower levels of intrusiveness, and have become increasingly affordable and accurate (for reviews, see Mukhopadhyay, 2015; Pantelopoulos & Bourbakis, 2008; Patel, Park, Bonatom Chan, & Rodgers, 2012). Mobility is essential to several live biofeedback application areas, such as exertion (Li et al., 2016; Mueller & Walmink, 2013; Walmink et al., 2013), driving (MacLean et al., 2013), gaming (Rani et al., 2005), and generally ubiquitous live biofeedback systems (Al Osman et al., 2013, 2016). In particular, a higher proportion of studies that employ wearable sensors use foreign live biofeedback systems than self live biofeedback systems presumably because studies typically use foreign live biofeedback applications in interaction scenarios that require higher mobility. However, several studies in the domain of self live biofeedback applications also employ wearable sensors (e.g., for drivers (MacLean et al. (2013) and swimmers (Li et al., 2016)).

The most widely used sensors for wearable live biofeedback systems include EDA (6 studies) (e.g., Gervais et al., 2016; Roseway et al., 2015) and PPG (2 studies) (e.g., Walmink et al., 2013). Studies often integrate wearable sensors to measure EDA into wristbands or wristwatches (Gervais et al., 2016; Howell et al., 2016; Roseway et al., 2015; Sakakibara et al., 2013; Snyder et al., 2015; Stach, Graham, Yim, & Rhodes, 2009; Walmink et al., 2013). As for PPG, several other live biofeedback applications derive heart rate from pulse activity measured with a clip mounted to the finger (Chittaro & Sioni, 2014) or the ear (Mueller & Walmink, 2013). Further, recent advances in signal processing may enable one to use contactless PPG measurements by using video cameras to analyze momentary color variations in the human skin (Rouast et al., 2016). Especially for ECG measurements, new mobile sensor technology (e.g., integrated into patches or t-shirts) has become more accessible.

5 User Interface

5.1 Overview of User Interfaces Used in Live Biofeedback Literature

As the receiver component of a live biofeedback system, the user interface conveys the feedback to users by addressing at least one of their senses. Based on our review, we found that the most common user interfaces used in the literature provide visual (48+19)[7], auditory (16+3), and tactile (4+2) forms of feedback. Some studies use a combination of these manifestation types in their user interfaces, such as virtual or physical alterations in game mechanics (10+2; e.g., Liu et al., 2009; Oertel, Kaiser, Voskamp, & Urban, 2007; Huang & Luk, 2015; Marshall et al., 2011). The level of obtrusiveness of the provided feedback should depend on the application domain and, thus, suit the user's environment. For instance, systems designed to interrupt the user for stress management (e.g., Al Osman et al., 2013, 2016) require a higher level of obtrusiveness than systems that facilitate social interactions (e.g., Roseway et al., 2015; Snyder et al., 2015). With respect to user interfaces that address a combination of senses, Stein and Meredith (1993) found that users perceive multisensory stimuli more strongly than unisensory stimuli if they arise from approximately the same location at approximately the same time and the user interface presents them in isolation.

5.2 Visual Feedback

Most live biofeedback applications provide visual feedback. One popular approach for visual biofeedback involves displaying elements that represent human physiology such as heart- or lung-shaped images (Tan et al. 2014), clip arts of groups of people (Fernández et al., 2013), stick men (Tennent et al., 2011), or a Pinocchio with a changing nose size (Al Mahmud et al. 2007). Studies that use human elements in live biofeedback visualization do so based on the rationale that such elements help non-expert users intuitively interpret the provided information (Tan et al., 2014). Al Mahmud et al. (2007) found that even children have no problems in interpreting human elements that represent physiological feedback. Another approach for visualizing live biofeedback employs nature-inspired elements, such as trees (Al Osman et al., 2016), water ripples (Slovák et al., 2012), flowers (Feijs et al., 2013), or butterflies (MacLean et al., 2013). Nature-inspired elements often serve as an analogy, such as using the health status of a tree (Al Osman et al., 2016) or the opening and closing of a flower (Feijs et al., 2013) to represent the user's current stress level. In some subject areas, such as information systems or computer science, studies provide more detailed feedback through meters, scales, or bars (Al Osman et al., 2013; Astor et al., 2013; Curmi et al., 2013). These more complex visual representations may require specific training (Al Osman et al., 2013).

5.3 Auditory and Tactile Feedback

Auditory biofeedback is the second most widely-used form of feedback. It is frequently based on nature-inspired sounds, such as the splash of a waterfall (Millings et al., 2015) or the sound of a beating heart (Chittaro & Sioni, 2014; Dekker & Champion, 2007). More than half of the systems that employ auditory biofeedback support wellbeing (11 of 19 studies) and about two thirds combine auditory feedback with visual feedback (12 of 19 studies). In these studies, live biofeedback systems provide information by altering the volume so that the music sounds "thin and distant" (Rijken et al., 2016, p. 424), pitch (Chandler, Bodenhamer-Davis, Holden, Evenson, & Bratton, 2001; Schnädelbach et al., 2012), and frequency (Chandler et al., 2001; Chittaro & Sioni, 2014; Vieira et al., 2016).

Six of the reviewed studies employ *tactile* biofeedback via vibration. Studies use tactile user interfaces when users need to receive information about their physiological state without distracting them from their primary task (Nishimura et al., 2007) or if one cannot easily employ other feedback manifestations due to the users' activity (e.g., during swimming (Li et al., 2016) and running (Curmi et al., 2013)). Furthermore, one could use tactile feedback to discretely provide a user with information; however, no researchers report choosing tactile feedback for this reason in any study. Usually, studies combine tactile feedback with other feedback manifestations such as visual feedback (Curmi et al., 2013; Huang & Luk, 2015; Schnädelbach et al., 2010, 2012) and auditory feedback (Schnädelbach et al., 2010, 2012). Ueoka and Ishigaki (2015), who focused on amplifying horror emotions during gaming, and Li et al. (2016), who tried to support efficient trunk rotation of swimmers, conducted the only two studies in our review that provide

[7] Abbreviated as before: number of papers on self live biofeedback + number of papers on foreign live biofeedback.

biofeedback exclusively as tactile biofeedback. The authors chose tactile feedback in both cases since it does not distract users from their primary task (i.e., gaming and swimming). Interestingly, all studies that investigate live biofeedback with a tactile feedback manifestation in the user interface have appeared only recently (the earliest study appeared in 2010).

5.4 Combinations and Other Forms of Feedback

In line with the notion that the human brain gathers information from multiple senses to accurately capture a situation (Ernst & Bülthoff, 2004), 25 of 76 studies use a combination of multiple live biofeedback manifestations in their user interface. Interestingly, all live biofeedback systems that employ user interfaces based on multiple feedback manifestations include visual feedback and combine it with, for example, tactile feedback (Huang & Luk, 2015), auditory feedback (Davis et al., 2005), or auditory and tactile feedback (Schnädelbach et al., 2010). Still, the majority of studies (51 of 76 studies) employ user interfaces based on only one type of live biofeedback manifestation (e.g., 42 studies provide only visual feedback). Furthermore, 21 studies address two senses and four studies address three senses through their user interfaces. Since one cannot easily implement *gustatory* and *olfactory* biofeedback systems with real-time feedback, they are correspondingly rare in literature. In fact, in the scope of this literature review, we found no system for gustatory or olfactory live biofeedback[8].

6 User Perception

6.1 Overview of User Perception Investigated in the Live Biofeedback Literature

By canalizing the impact that the receiver component of a live biofeedback system has on the user, user perception forms the central part of the destination component. Affecting user perception can be a goal in and of itself (e.g., improving user experience, increasing stress awareness). However, changing user perception can also be a vehicle to help them regulate their physiological activity (see Section 7) and changes in user behavior (see Section 8). As we discuss in Section 2.5, we can distinguish two different categories of focal constructs that live biofeedback systems address. First, in terms of constructs that are *directly* linked to physiological activity, live biofeedback systems commonly address the perception of stress (27 studies), perception of physiology (10 studies), and specific emotions (9 studies). Second, in terms of constructs that are *indirectly* linked to physiological activity, live biofeedback systems commonly address social interaction (10 studies) and improving user experience (15 studies).

6.2 Constructs Directly Linked to Physiological Activity

The first category of user-perception constructs includes those constructs *directly* linked to physiological activity (e.g., perception of stress, physiology, and specific emotions). Live biofeedback systems that focus on these constructs commonly support users in managing stress and regulating their emotions by increasing their awareness of their internal state. Conceptually, these systems build on the psychophysiological principle that every change in a person's mind is accompanied by a change in the person's physiology (Green et al., 1970). Thus, for these live biofeedback systems, the measured physiological activity needs to accurately predict the respective construct as we outline in Section 3.2.

The relation between the user-perception construct and a person's physiological activity is comparatively simple in those studies that investigate the impact of self live biofeedback on enhancing users' perception of their physiology because they can provide information on the respective part of their physiology. Studies that focus on perception of physiology often employ relatively simple visual user interfaces such as light pulses for indicating the end of each inter-beat (R-R) interval obtained from a heart rate recording (Goldstein et al., 1977), a balloon that expands and contracts with the rhythm of respiratory frequency (Xiong et al., 2013), or screens that change their color and, thus, provide breathing instructions to support paced breathing (Pastor et al., 2008). By contrast, for live biofeedback systems that address perception of stress or specific emotions such as fear, the relation between the user-perception construct and the measured physiological activity is more complex. For instance, studies use cardiovascular (Millings et al., 2015; Rijken et al., 2016; Sakakibara et al., 2013), EDA (Feijs et al., 2013; MacLean et al., 2013; Matthews et al., 2015), and respiratory measures (Al Rihawi et al., 2014; Moraveji et al., 2011; Morie et

[8] The only study in the scope of this literature review remotely related to gustatory feedback evaluated a personalized sports drink based on heart rate data that the system generated for study participants and which they received after they finished their workout (Khot, Lee, Hjorth, & Mueller, 2015).

al., 2011) to assess stress. The range of approaches to address a user's stress perception corroborates Mauss and Robinson's (2009) statement that no "gold standard" for measuring a specific construct exists. Furthermore, live biofeedback systems that use physiological activity as a proxy for a specific construct face the difficulty of isolating the change in physiology that the construct causes from any other (environmental) influence in order to provide accurate and, thus, useful information. Despite all these challenges, several studies investigate live biofeedback systems in stressful contexts and demonstrate that live biofeedback can be an effective way to increase users' stress awareness (Fernández et al., 2013; Huang & Luk, 2015; Snyder et al., 2015). Supporting users in increasing their stress awareness is important because physiological stress reactions precede the conscious perception of stress levels (Adam, Gimpel, Maedche, & Riedl, 2017; Riedl, 2013).

6.3 Constructs Indirectly Linked to Physiological Activity

The second category of user-perception constructs incudes those constructs *indirectly* linked to physiological activity (e.g., social presence, user experience). Live biofeedback systems that studies apply in social interaction and serious/playful games frequently use constructs indirectly linked to physiology.

Game contexts range from virtual environments such as sports and fitness games (Buttussi et al., 2007; Nenonen et al., 2007), games on mobile devices (Reitz et al., 2012), and first-person shooter games (Dekker & Champion, 2007; Tennent et al., 2011) to games in real-world environments such as a rodeo amusement ride (Marshall et al., 2011), outdoor games (Magielse & Markopoulos, 2009; Mueller & Walmink, 2013), and tabletop games (Al Mahmud et al., 2007). Nacke et al. (2011) investigate the adaption of multiple game mechanics in the live biofeedback system such as the game character's speed, target size, or weapon reach and conclude that biosignal integration can result in a "more fun experience than using only a traditional control scheme for game interaction" (Nacke et al., 2011, p. 110). The authors derive two design implications for integrating live biofeedback into games: 1) the system designer should base action control in gameplay on physiological measures that underlie direct control (e.g., respiration (Tennent et al., 2011) and eye movement (Chollet et al., 2015)) and 2) the system designer should use physiological input underlying indirect control (e.g., heart rate, skin conductance level) to alter the game world. Furthermore, several studies map physiological measurements to game difficulty or intensity (Buttussi et al., 2007; Marshall et al., 2011; Nenonen et al., 2007; Reitz et al., 2012). Three studies investigate user experience outside a gaming context. Yu et al. (2016) examine surfaces as a shape-changing interface of live biofeedback and note that users find explicit mapping of physiological activity to the user interface (e.g., vibration associated to heart activity) the easiest to understand. Davis et al. (2005) found that users are excited about the integration of live biofeedback into artwork, and IJsselsteijn, De Kort, Westerink, De Jager, and Bonants (2004) report that a virtual coach with live biofeedback does not influence training intensity or enjoyment but lowers users' perception of pressure and tension and raises perceived control and competency.

Foreign live biofeedback systems (i.e., live biofeedback systems that also transmit foreign-to-self and/or self-to-foreign signals) frequently use user-perception constructs related to social interaction (e.g., social presence, social connectedness, and empathy) that are indirectly linked to physiological activity (Al Mahmud et al., 2007; Magielse & Markopoulos, 2009; Mueller & Walmink, 2013). These live biofeedback systems mostly use ECG (6 of 10 studies) to increase perceived social presence (Curmi et al., 2013; Gervais et al., 2016; Järvelä et al., 2016; Mueller et al., 2010; Roseway et al., 2015; Slovák, Tennent, Reeves, & Fitzpatrick, 2014). Additionally, studies use a visual user interface that represents a heart (Gervais et al., 2016; Järvelä et al., 2016) and/or heart rate as a number (Curmi et al., 2013; Järvelä et al., 2016; Slovák et al., 2012) to support the feeling of social presence because the heart is a central human organ.

6.4 Measurement of User Perception

To assess how live biofeedback affects user-perception constructs, studies use a variety of well-established and custom questionnaires. To measure the perception of stress-related constructs, studies use Kirschbaum, Pirke, and Hellhammer's (1993) Trier social stress test (Bouchard, Bernier, Boivin, Morin, & Robillard, 2012; Dillon, Kelly, Robertson, & Robertson, 2016), Cohen, Kamarck, and Mermelstein's (1983) perceived stress scale (Meier & Welch, 2016; Millings et al., 2015), Spielberger, Gorsuch, Lushene, Vagg, and Jacobs's (1983) state trait anxiety inventory (Feijs et al., 2013; Meier & Welch, 2016; Reynolds, 1984; Sakakibara et al., 2013), Matthews et al.'s (2002) Dundee stress state questionnaire (Tan et al., 2014), and Lesage, Berjot, and Deschamps's (2012) visual analogue scale of perceived stress (Al Osman et al., 2016). Furthermore, studies measure perceived stress and the congruence of users' stress perception and the live biofeedback using questions on a seven-point Likert scale (e.g., "The character's relaxation level corresponded to mine" in Chittaro & Sioni, 2014, p. 670).

To evaluate emotional states in general, studies use Bradley and Lang's (1994) self-assessment manikin (Järvelä et al., 2016; Peira et al., 2014) and Thayer's (1986) activation deactivation adjective checklist (Meier & Welch, 2016). Some studies use Gross and John's (2003) emotion regulation questionnaire to assess users' emotion regulation strategies (Astor et al., 2013; Jercic et al., 2012). To assess the relationship between personality traits, affective states, affect-management strategies, and reactions to emotional regulation demands at work, Roseway et al. (2015) use a combination of three well-established measures: emotional intelligence (Salovey & Mayer, 1990), the big five personality inventory (Goldberg, 1990, 1993), and the self-monitoring questionnaire (Snyder, 1974). With respect to interpersonal evaluations, Järvelä et al. (2016) use an unpublished set of 17 items from Biocca and Harms (2003) in the context of social presence to measure co-presence, attentional engagement, emotional contagion, comprehension, and behavioral interdependence. Furthermore, other studies use open-ended interviews to assess study participants' experiences with respect to system interaction and perceptions on social interaction (Curmi et al., 2013; Mueller et al., 2010; Walmink et al., 2013).

To assess live biofeedback systems in general, studies use IJsselsteijn, Poels, and De Kort's (2007) game experience questionnaire and modified versions of Brooke's (1996) system usability scale (Cederholm et al., 2011; Hilborn et al., 2013; Jercic et al., 2012). Tan et al. (2014) use the NASA task load index (Hart & Staveland, 1988) to measure mental workload. Furthermore, studies use interviews (Moran et al., 2016) and custom questionnaires to assess user experience and a variety of system characteristics, such as accuracy, engagement, intrusiveness, and the usefulness of the live biofeedback systems (Al Mahmud et al., 2007; De Oliveira & Oliver, 2008; Muñoz et al., 2016; Roseway et al., 2015; Snyder et al., 2015; Stach et al., 2009).

7 Regulation of Physiological Activity

7.1 Overview of Regulation of Physiological Activity Investigated in the Live Biofeedback Literature

Many live biofeedback systems focus on supporting users in regulating their physiological activity and, hence, regulation is an important part of the destination component. The reviewed studies assist users to alter their physiology (10 studies), engage in stress management (27 studies), and regulate their emotions (9 studies). The majority of live biofeedback systems that focus on supporting users in regulating their physiological activity exclusively focus on transmitting self-to-self signals (self live biofeedback; 41 of 46 studies). However, five studies use foreign live biofeedback—all in the stress-management domain. Furthermore, we found that 27 of all live biofeedback systems that assist users in regulating their physiological activity focus on increasing their wellbeing, and the studies apply them in various settings (e.g., seven in a game context, three in a physical exercise context, three in an economic context, and two in a communication context).

7.2 Increasing Control of Physiological Activity

Studies that focus on increasing users' control of their physiological activity frequently employ cardiovascular measures such as heart rate (e.g., Goldstein et al., 1977; Höysniemi et al., 2004; Lehrer et al., 2003; Masuko & Hoshino, 2006; Ueoka & Ishigaki, 2015) and/or heart rate variability (Ebben et al., 2009; Lehrer et al., 2003; Sakakibara et al., 2013). Goldstein et al. (1977) found that providing self live biofeedback during exercise can support users in effectively lowering their heart rate and blood pressure. Schnädelbach et al. (2010, 2012) and Lehrer et al. (2003) found that self live biofeedback can support users in increasing their heart rate variability. Pastor et al. (2008) found that self live biofeedback can effectively help users to learn how to control their physiological responses but only if precise instructions accompany the self live biofeedback.

7.3 Stress Management

About one third of all reviewed live biofeedback systems (22+5) support users in managing their stress levels. From a theoretical perspective, one can link live biofeedback-based stress-management systems back to Lazarus and Folkman's (1987) transactional model of stress. This model conceptualizes stress as an emotion that emerges from an emotion-generative process that comprises causal antecedents (personal and environmental variables), mediating/moderating processes (appraisal and coping), and immediate effects (affect, physiological changes, outcome quality) (Lazarus & Folkman, 1987). Live biofeedback systems that focus on improving stress perception often use serious or playful games (Al Osman et al., 2016; Al Rihawi et al., 2014; Buttussi et al., 2007; Chittaro & Sioni, 2014; Tennent et al., 2011) with lean user interface elements, such as a bar that moves across the screen (Moraveji et al., 2011) or ambient light (Matthews et al., 2015; Snyder et al., 2015).

However, the live biofeedback studies on stress management present mixed results. MacLean et al. (2013), for example, found that drivers who wore the self live biofeedback application MoodWings, a bracelet that reflects stress, drove more safely but experienced more stress (physiologically and self-perceived) than drivers in the control group. By displaying users' physiological state through colored ambient light, Matthews et al.'s (2015) self live biofeedback application Moodlight also focuses on helping users manage their stress. However, Matthews et al. found that "feedback that displays systematic progress towards relaxation regardless of the users' level of physiological relaxation" (p. 605) helps users reduce stress better than self live biofeedback. Millings et al. (2015) report that integrating self live biofeedback into a stress-management program reduces its effectiveness. Moraveji et al. (2011) investigated a peripheral self live biofeedback application that helps users pace respiration but found that they did not sustain the initial decreases in their breathing rate. Chittaro and Sioni (2014) tested user perception of multimodal and unimodal self live biofeedback against placebo self live biofeedback and found that only the unimodal self live biofeedback proved significantly more accurate than the placebo self live biofeedback application.

In contrast to the findings above, several studies provide evidence that live biofeedback effectively helps users to manage their stress. In a business context, Al Osman et al. (2013) present a stress-management application for office workers that provides a feedback response when stress levels reach a threshold with detection accuracy of nearly 90 percent. In this sense, information systems can become stress-sensitive and "trigger context-sensitive interventions" (Adam et al., 2017, p. 281). In a second study, Al Osman et al. (2016) observe that subjects maintain more control over their mental stress when they receive live biofeedback. Bouchard et al. (2012) report that their live biofeedback-based stress-management application reduces stress, and Chandler et al. (2001) report that their live biofeedback-assisted relaxation application for counselor trainees helps users reduce their stress levels and results "in a greater sense of personal well-being" (p. 1). Studies that combine live biofeedback with meditation tasks or autogenic training identify live biofeedback as a useful tool for helping users to relax and reduce their heart rate (Zeier, 1984) and to detect affect (Reynolds, 1984). Morie et al. (2011) demonstrate that their live biofeedback system reduces user distress while running, and Feijs et al. (2013) notes that their live biofeedback application for breast milk expression helps mothers to relax and, thus, to produce and eject more milk in shorter time intervals. Two studies investigate the commercial stress-reduction product StressEraser[9] and report that live biofeedback significantly increases sleep quality (Ebben et al., 2009) and cardiorespiratory function during sleep (Sakakibara et al., 2013). Furthermore, using the ambient lighting system MoodLight (see also Matthews et al., 2015), Snyder et al. (2015) explore how EDA measurements can help users to manage their stress in social contexts. Results imply that subjects can use the system as a tool for self-revelation in order to create a connection with their counterparts. Tan et al. (2014) study the effect of live biofeedback in video-mediated work and report that providing an instructor with foreign live biofeedback of a worker leads to reduced levels of mental workload in the worker and improved task performance.

These mixed results on the usefulness of live biofeedback for stress management reveal that the success of live biofeedback systems depends on 1) its components, 2) the primary task, and 3) environmental factors. With respect to the components, we found that measuring multiple physiological activities does not necessarily result in a more accurate and, thus, a more effective stress-management system but perhaps even a more obscure and perceived as less accurate. Furthermore, conspicuous and obtrusive feedback manifestations can even result in increased instead of reduced stress levels. We also found that successful live biofeedback systems do not deter users from their primary tasks and consider environmental factors, such as social contexts and sensational requirements.

[9] The StressEraser (http://www.stress.org/certified-product-stress-eraser) is a portable self live biofeedback device based on heart rate variability measurements that The American Institute of Stress developed.

7.4 Emotion Regulation

Studies on stress management primarily focus on the arousal dimension of emotion. Complementarily, several live biofeedback studies (9) extend this focus to the valence dimension (Cederholm et al., 2011; Hilborn et al., 2013; Jercic et al., 2012; Nasoz, Lisetti, & Vasilakos, 2010; Peira et al., 2014) and the application of specific emotion regulation strategies (Astor et al., 2013; Hicks et al., 2014; Hilborn et al., 2013; Jercic et al., 2012; Peira et al., 2014). All these studies exclusively employ self-to-self transmission signals. Emotion regulation theory builds on the assumption that emotions emerge in an emotion-generative process in which an emotion's extent and magnitude (e.g., anger, fear) and its behavioral consequences (e.g., impulsive behavior) depend on the way it is regulated by the person who experiences it (Gross & John, 2003). Hence, studies often situate live biofeedback systems for emotion regulation in scenarios that will potentially trigger high levels of arousal and have detrimental effects on decision making (e.g., driving (Nasoz et al., 2010) and financial decision making (Astor et al., 2013)).

The reviewed studies support the notion that live biofeedback can be an effective tool for emotion regulation. Peira et al. (2014), for example, report that heart rate-based changes of the user interface background color (i.e., green background for decreasing heart rate and red background for increasing heart rate) support emotion regulation in response to the display of negatively valenced image stimuli. Furthermore, several studies show that using serious games with biofeedback can be helpful to train users' emotion-regulation capabilities (e.g., Cederholm et al., 2011; Hilborn et al., 2013; Jercic et al., 2012)[10]. These studies alter game mechanics based on heart rate (Astor et al., 2013; Hilborn et al., 2013; Jercic et al., 2012) or skin conductance (Cederholm et al., 2011; Hicks et al., 2014) to reward the regulation of physiological states. Studies on serious games that incorporate self live biofeedback show that live biofeedback systems can detect specific affective states (e.g., of anxiety or engagement) in real time and use adjustments of game difficulty (based on the detected affective state) to support emotion regulation and enhance user experience and performance (Liu et al., 2009; Rani et al., 2005).

8 User Behavior

8.1 Overview of User Behavior Investigated in the Live Biofeedback Literature

Studies often apply live biofeedback systems that focus on triggering behavior change in the context of social interaction (19), games (14), and physical exercise (9). Furthermore, seven studies focus on changing user behavior in other contexts, such as in training/learning (Chollet et al., 2015; Friedman, Suji, & Slater, 2007) and economic decision making (Fernández et al., 2013). In all contexts, however, live biofeedback applications primarily focus on supporting a desired behavior change such as increased or more effective physical activity and enhanced social interaction.

8.2 Physical Exercise

Worldwide, one out of four adults is not active enough, which is one of the main contributing factors for non-communicable diseases (WHO, 2017). As such, many sports and fitness games use live biofeedback systems to increase user engagement and the effectiveness of the respective physical exercise. Höysniemi et al. (2004) and Masuko and Hoshino (2006) build on exercise programs that include game elements to encourage regular exercise (Mokka, Väätänen, Heinilä, & Välkkynen, 2003). They evaluate live biofeedback in fitness games and report that it improves users' sense of accomplishment and helps users to maintain an optimal heart rate for the respective exercise, which increases the exercise's effectiveness. De Oliveira and Oliver (2008) report foreign live biofeedback to be a driver of competition in a running exercise experience in which runners receive information on each other's heart rates via a mobile device. Stach et al. (2009) found that their foreign live biofeedback mechanism did not significantly affect engagement during gameplay or average speed. Their results, however, indicate that foreign live biofeedback reduces the performance gaps between people of different fitness levels. Similar to Stach et al. (2009), Magielse and Markopoulos (2009) found that their live biofeedback game did not alter engagement in the physical exercise.

[10] Four of these studies belong to the project xDelia (Astor et al., 2013; Cederholm et al., 2011; Hilborn et al., 2013; Jercic et al., 2012). xDelia (http://www.xdelia.org) is an interdisciplinary project funded by the European Commission with contributions from various European research institutions and businesses that investigate emotion-centric financial decision making and learning.

8.3 Social Interaction

People have a limited ability to (correctly) assess other people's mental states (i.e., mentalizing) and interpret social cues, which is vital for social behavior (Decety, Jackson, Sommerville, Chaminade, & Meltzoff, 2004; Frith & Frith, 2006; Joseph & Newman, 2010; Lim & Reeves, 2010; Mayer, Roberts, & barsade, 2008; Polosan et al., 2011). Thus, several studies (eight out of 18 studies) explore how one can use foreign live biofeedback to support users in better assessing others' mental state (Gervais et al., 2016; Slovák et al., 2012)—even when the other people are not physically present (Curmi et al., 2013; Fernández et al., 2013; Howell et al., 2016)—and how one can amplify social cues and/or people's sensitivity towards such cues based on foreign-to-self signals. In this vein, studies provide live biofeedback as a means to convey social cues in order to facilitate the mentalizing process and foster social interaction (see also Section 6.3). Building on this theoretical pathway, studies investigate foreign live biofeedback as a driver for social interaction (Al Mahmud et al., 2007; Howell et al., 2016), social connectedness (Curmi et al., 2013; Slovák et al., 2012), social experience (Mueller et al. 2010), social engagement (Snyder et al., 2015), or social support (Walmink et al., 2013).

Studies often implement live biofeedback systems for social interaction by using ambient or wearable devices. Such devices facilitate foreign and self live biofeedback at the same time because users (both self and other) can potentially perceive them. Gervais et al. (2016) found that ambient live biofeedback devices can ease social interaction, foster empathy and relaxation, and promote self-reflection (Gervais et al., 2016). Järvelä et al. (2016) report increased heart rate synchrony for dyads at different geographical locations. Roseway et al. (2015) report that their BioCrystal system resulted in users' more highly recognizing their physiological states and supported interpersonal communication (Roseway et al., 2015). Slovák et al. (2012) found that heart rate sharing does not improve feelings of closeness in the workplace. With Howell et al.'s (2016) wearable foreign live biofeedback t-shirt, pairs of friends can share emotions, such as joy or embarrassment. Wearable live biofeedback systems support users to enact social performances such as emotional engagement. Picard and Scheirer (2001) observe that users enjoy using the glove-like Galvactivator device and try to make each other's foreign live biofeedback devices light up. Due to the ambiguity of the feedback, the authors found that the device often led to conversations about the wearer's feelings. Generally, when providing ambient or wearable live biofeedback for social interaction, one needs to consider users' willingness to share their private physiological information (Slovák et al., 2012).

9 Knowledge Gaps and Directions for Further Research

This review reveals several research gaps in the literature, which suggests five promising directions for further research. In this section, we summarize each direction. Importantly, these directions each require individual research attention in terms of closing specific knowledge gaps and research oversight in terms of how advances in a specific research stream (e.g., user interfaces) affect results in another stream (e.g., technology acceptance). As live biofeedback research progresses, further directions with dedicated foci will emerge, such as group feedback or unconscious feedback processing.

9.1 Direction 1: Measurement Tools and User Interfaces

A key design question for live biofeedback applications involves selecting 1) the measurement tools to circulate the feedback and 2) the manifestation that the user interface uses to convey the feedback to the user. Our review reveals that the majority of studies employ visual (88%) and/or auditory (25%) manifestations. However, current research certainly does not cover the full range of conceivable feedback manifestations and combinations thereof. Especially against the backdrop of wearable devices, it appears that tactile manifestations deserve further research attention because few reviewed studies investigate this type of feedback (for exceptions, see Curmi et al., 2013; Huang & Luk, 2015; Schnädelbach et al., 2012, 2010; Ueoka & Ishigaki, 2015). Tactile feedback may be a particularly effective way to draw user attention during tasks when other sensory channels such as vision or hearing are occupied (Damian & André, 2016; Lee & Starner, 2010). Furthermore, research on sensory substitution shows the potential to transmit large and complex amounts of information to a receiver through unconscious processing from tactile stimulation patterns (Novich & Eagleman, 2015; Shull & Damian, 2015). Building on the elements of the integrative framework (source, transmitter, receiver, and destination), a systematic evaluation of measurement tools should consider the limitations of people's perception (Baumeister, Bratslavsky, Muraven, & Tice, 1998; Miller, 1956), how they will interpret the provided feedback response (e.g., manifestations resembling human features versus nature-inspired elements), and how that will lead to changes in behavior.

9.2 Direction 2: Construct Validity

We need more research to better understand the relations between physiological features, user interfaces, and target variables. Specifically, research needs to evaluate whether the combination of all elements of a live biofeedback application, from the underlying biosignal (source) over the measurement tool (transmitter) to the user interface (receiver), addresses the identified constructs to achieve the desired effects on the user and their environment (destination). For instance, live biofeedback applications may affect other perceptual and behavioral variables than intended (e.g., driving safety (MacLean et al., 2013) and perceived ambiguity (Mueller & Walmink, 2013)). Hence, similar to the original purpose of Shannon and Weaver's (1949) transmission model for communication, research needs to validate the effectiveness in terms of "the success with which the meaning is conveyed to the receiver" (Shannon & Weaver, 1949, p. 5). Studies that systematically vary single elements of live biofeedback systems could provide further insights into the degree to which they affect specific constructs such as stress or emotional arousal. We need research that validates physiological measures for live biofeedback response generation (e.g., by applying Ortiz de Guinea, Titah, and Léger's (2013) multi-trait multi-method matrix or examining the relationship between those physiological measures and psychological measures (Tams, Hill, & Thatcher, 2014)) to ensure that the live biofeedback response bears information about the identified construct.

9.3 Direction 3: Context Dependence

In their design guidelines for integrating biosignals into information systems, Astor et al. (2013) emphasize that the chosen biosignals need to be "adequate for the environment of the users" and that the user interface needs to consider the "contextual and situational circumstances of the users" (Astor et al., 2013, p. 268). All studies covered in our review examine one specific live biofeedback application in one specific scenario (e.g., communication, decision making, games), which leads to findings that are difficult to compare or that may even contradict each other. For example, while some studies demonstrate that one can use live biofeedback to reduce stress levels in a specific context (Al Osman et al., 2016; Al Rihawi et al., 2014), others do not note a lasting effect (Moraveji et al., 2011) or note that live biofeedback increases users' stress levels (MacLean et al., 2013). Our review reveals that researchers have not yet conducted a structured evaluation that investigates the interdependencies between biosignals, measurement tools, transmission signal directions, live biofeedback interfaces, and the effect on the users with respect to environmental conditions in an information systems setting. In this sense, we can draw no conclusions on whether a live biofeedback application that increases performance in one task (e.g., gaming) also increases performance in another task (e.g., trading) or whether it may in fact be detrimental to performance in that task. Future research needs to investigate when and under which circumstances one can successfully transfer a live biofeedback application from one context to another.

9.4 Direction 4: Interplay of Self and Foreign Live Biofeedback

While research on foreign live biofeedback is relatively scarce compared to self live biofeedback, the existing studies on foreign live biofeedback show that these systems can be an interesting and promising approach for many different application domains such as communication (Picard & Scheirer, 2001), games (Al Mahmud et al., 2007), and economic decision making (Fernández et al., 2013). Due to increasing connectedness of individuals, the impact of social media, the need for remote collaborations, and the availability of wearable sensors, foreign live biofeedback will continue to gain importance. Similarly, only two studies investigate group feedback (i.e., feedback for more than two people) (Fernández et al., 2013; Järvelä et al., 2016), but it will likely become more relevant in the future. Further, because researchers have conducted most studies on foreign live biofeedback in computer science (95%), we need future research in subject areas such as information systems and psychology to improve our understanding of how people interact with and are affected by foreign live biofeedback systems. Few studies explicitly investigate both self live biofeedback and foreign live biofeedback. One could use the concept of the transmission signals, which specify whether users (self) receive the feedback response or other users do (other) (see Figure 2), to systematically evaluate the interplay of self live biofeedback and foreign live biofeedback. In this vein, a systematic evaluation could provide insights whether the same combination of biosignals, neuroIS methods, user interfaces, and psychological constructs yields similar results in self live biofeedback and foreign live biofeedback systems. Furthermore, we note that, while self live biofeedback and foreign live biofeedback applications use nearly the same biosignals, neuroIS methods, and user interfaces, the target constructs differ.

9.5 Direction 5: Technology Acceptance

Live biofeedback applications raise a range of important questions of technology acceptance. First, hardly any research examines how acceptable it is for users to see feedback on their own physiological data and how appropriate designs may increase the level of perceived usefulness. For instance, Astor et al. (2013) found that some users reported that they did not find self live biofeedback useful in regulating their emotional state. Yet, the data shows that users who receive live biofeedback in fact exhibit more effective emotion regulation, which leads to the conclusion that “biofeedback is to some extent processed unconsciously” (Astor et al., 2013, p. 268). Furthermore, users might be more willing to accept live biofeedback if they are in control of it; that is, if they can 1) switch the feedback on and off or 2) determine the type of the feedback manifestation in the user interface and the level of feedback obtrusiveness. Second, technologies such as remote photoplethysmography (Rouast et al., 2016) enable physiological measurements and, hence, foreign live biofeedback, that researchers can conduct without the awareness of the sender (e.g., by analyzing video data gained from cameras integrated into head-mounted devices such as Google Glass or Microsoft HoloLens). This development raises important questions around involuntary surveillance and privacy invasion associated with physiological measurements (Fairclough, 2014) and how it affects the technology acceptance of foreign live biofeedback applications both from the sender and the receiver perspective.

10 Discussion and Conclusions

10.1 Summary of Results

In their application strategies of neuroIS methods in design science research, vom Brocke et al. (2013) concluded that information systems research should explore using “neuroscience tools as built-in functions of IT artifacts” (vom Brocke, Riedl, & Léger, 2013, p. 3). As one important application domain of such neuro-adaptive systems, live biofeedback systems enable users to obtain insight into their own or other persons’ physiological processes for everyday use. While researchers have examined live biofeedback primarily in the clinical domain, a growing number of studies employ it in non-clinical domains such as decision making, education, and games. As such, self and foreign live biofeedback offer a promising avenue for information systems research and practice. Hence, in this paper, we develop an integrative framework for live biofeedback and systematically review the fragmented literature on the topic that entails 76 studies published in computer science, engineering and technology, information systems, medical science, and psychology. The review provides insights into the elements of live biofeedback applications and comprehensively overviews live biofeedback applications in non-clinical domains. It covers both 1) studies on self live biofeedback systems that address the effects of live biofeedback on perception, behavior, and regulation of physiological activities *within* a person and 2) studies on foreign live biofeedback systems that address social interactions *between* individuals. Based on these studies, we identify key theories and focus variables and synthesize research results for both self and foreign live biofeedback.

In total, we found 55 studies on self live biofeedback and 21 studies on foreign live biofeedback. While most studies clearly examine self live biofeedback, the concepts applied in foreign live biofeedback studies show strong similarities with respect to biosignals, measurement tools, and user interfaces and build strongly on the established self live biofeedback literature. The majority of studies on self and foreign live biofeedback focus on visual biofeedback (87% of self and 90% of foreign live biofeedback studies). Colors play a key role for both self (Jercic et al., 2012) and foreign live biofeedback (Fernández et al., 2013). Human elements (e.g., a heart or a pair of lungs (Hicks et al. 2016)) or nature-inspired elements (e.g., a flower (Feijs et al., 2013) and water ripples (Slovák et al., 2012)) and vibrations (Huang & Luk, 2015; Schnädelbach et al., 2010) are also popular for both kinds of live biofeedback. However, self and foreign live biofeedback differ in their theoretical underpinnings. One can broadly categorize the psychological constructs they target as those that focus on the regulation of physiological activity (e.g., emotion regulation, stress management), user perception that is directly or indirectly linked to physiological activity (e.g., stress perception, user experience), and user behavior (e.g., physical exercise, social interaction). In terms of the theories employed to address these constructs, we found that self live biofeedback systems primarily build on the psychophysiological principle of the body-mind loop that Green et al. (1970) introduced and related theories of stress management, emotion regulation, and individual user experience. Due to their inherent social connotation, foreign live biofeedback systems extend the theoretical basis and build primarily on theories of social presence (Hess, Fuller, & Campbell, 2009), social connectedness (Curmi et al., 2013; Slovák et al., 2012), and mentalizing (Decety et al., 2004; Frith & Frith, 2006).

Taken as a whole, this study comprehensively reviews the various different applications of live biofeedback in non-clinical settings. We found that many studies on self live biofeedback focus on constructs directly associated with physiological activity and that support users in regulating their underlying physiological states: 40 percent of self live biofeedback studies focus on stress management (e.g., Al Osman et al., 2016; Al Rihawi et al., 2014), 18 percent on direct alternation of users' physiology (e.g., Masuko & Hoshino, 2006; Pastor et al., 2008), and 16 percent on emotion regulation (e.g., Astor et al., 2013; Cederholm et al., 2011). Studies on foreign live biofeedback, however, focus on using live biofeedback as a means to convey social cues between the feedback sender and the feedback receiver in order to facilitate changes in human behavior related to social interaction (48%) (e.g., Picard & Scheirer, 2001; Slovák et al., 2012; Tan et al., 2014), games (29%) (e.g., Al Mahmud et al., 2007; Huang & Luk, 2015; Stach et al., 2009), and physical exercise (14%) (e.g., De Oliveira & Oliver, 2008; Mueller & Walmink, 2013).

This review has some limitations that readers should consider. Since we focus on providing a general and comprehensive overview on existing literature on live biofeedback applications for consumers in everyday use, we limited our search scope to 1) healthy subjects, 2) non-clinical domains, and 3) physiological activity measures of the peripheral nervous system. The review only includes studies that provide some level of qualitative and/or quantitative evaluation (excluding work such as Djajadiningrat et al. (2009) and Hudlicka (2009), which present no evaluation). Since we investigated a body of highly fragmented literature, we conducted a fragmented literature review, which included backward and forward searches, and focused on a broad range of outlets with keywords pertinent to different types of live biofeedback systems. However, as the body of live biofeedback literature in non-clinical domain grows, systematic reviews of the literature and applications in distinct research domains will become necessary.

10.2 Implications for Practice

In summary, one can employ self and foreign live biofeedback in various different domains that range from individual settings such as immersive elements in computer games, stress-management tools, and emotion regulation training to systems that support remote group collaborations in social settings. Our review reveals several design considerations for integrating live biofeedback into information systems, each of which depends on situational factors and the characteristics of the user's primary task.

First, system designers need to consider the *time frame* available for 1) calculating the underlying physiological features of the live biofeedback (e.g., heart rate) and 2) conveying the feedback to the user. While fast-paced decision environments may only allow time frames of several seconds (e.g., financial trading (Fernández et al., 2013) and driving (Nasoz et al., 2010)), other decision scenarios allow longer time frames of up to several minutes (e.g., certain aspects of stress-management training). The available time frame determines the range of available biosignals and measurement tools that the system designer can choose from as the source for the feedback. For instance, some techniques for determining changes in skin conductance level may require several minutes or hours (Boucsein, 2012; Dawson, Schell, & Filion, 2007), and all real-time frequency analysis of heart rate in the reviewed studies adopted a time frame of at least 30 seconds (Al Osman et al., 2013, 2016; Lehrer et al., 2003).

Second, system designers need to consider the desired level of *feedback obtrusiveness* in addressing one or more of the five sensory channels. Some decision scenarios may require actively disrupting users' decision making process (e.g., in order to avoid impulsive decisions in the "heat of the moment") (Loewenstein, 1996, p. 286). Importantly, however, instead of reducing stress, users may perceive obtrusive feedback as distracting and even more stressful (MacLean et al., 2013; Slovák et al., 2012), which may lead to adverse outcomes in terms of user experience and decision outcomes. The desired level of feedback obtrusiveness can be crucial for the success of a live biofeedback system as the conflicting results of self live biofeedback applications for stress management evidence. In choosing the level of feedback obtrusiveness, one also needs to consider whether people other than the intended feedback recipient could (or should) perceive the feedback. Certain forms of feedback (e.g., auditory feedback) may inadvertently be conveyed to third parties with detrimental effects for the original feedback receiver (e.g., increased stress from being in the social spotlight).

Third, the various forms of measurement tools and user interfaces allow for different levels of *feedback complexity*. While some studies employ user interfaces that convey low levels of complexity and use intuitive elements resembling human (e.g., heart and breathing activity (Tan et al., 2014)) or natural features (e.g., water ripples or flowers (Feijs et al., 2013; Slovák et al., 2012)), other studies employ more complex user interfaces such as meters (e.g., Jercic et al., 2012). Furthermore, live biofeedback employed through dedicated UI artifacts (e.g., in stress-management applications, Al Osman et al., 2013) is often more complex than live biofeedback provided though the adaption of existing UI elements (e.g., in playful games (Nacke et al., 2011)). Therefore, one needs to carefully consider the level of complexity against the characteristics of the primary task and users' skills. For instance, Jercic et al. (2012) found that most participants did not pay attention to a radial arousal meter in the top-right corner of the screen due to the fast-paced nature of the decision environment and the complexity of the arousal meter. In that study, participants preferred the use of overlay elements added to the center of the screen where colors indicated their arousal levels. Hence, system designers need to set a level of feedback complexity that acknowledges users' level of attention and processing to understand the provided feedback in a given context. Importantly, using a combination of different feedback types is not necessarily more effective than a single feedback type, although researchers generally assume that the human brain can process more information if it is transmitted to multiple sensory channels (Ernst & Bülthoff, 2004). Schnädelbach et al. (2010), for example, applied a combination of visual, auditory, and tactile biofeedback elements, but participants did not find the visual feedback elements useful.

Fourth, system designers need to consider the *level of control* that the user has and/or should have over the physiological activity measure used as system input. While the autonomous nervous system modulates some biosignals (e.g., EDA, heart rate) and, therefore, individuals can only indirectly control them, individuals can largely directly control other biosignals (e.g., body movements, respiration) (Riedl et al., 2014). Hence, practitioners need to define the level of control the user should have over the measured physiological activity for a given purpose (e.g., decision support, entertainment, stress management) and consider both the physiological characteristics of the biosignal and the skill set of the target audience to control the biosignal. Nacke et al. (2011) conclude that, with respect to user experience in gaming, one should use biosignals that users can directly control due to their visible responsiveness. They note that users consider biosignals that they can control only indirectly as slow and inaccurate and that they do not adequately allow users to alter the game environment. For some application domains, such as stress management and emotion regulation training applications, however, gaining higher levels of control of the underlying biosignal constitutes the live biofeedback application's actual purpose. Hence, such applications often focus on biosignals over which the user has only indirect physiological control (e.g., Al Osman et al., 2013, 2016; Howell et al., 2016).

Finally, and most importantly, system designers need to consider the level of *meaningfulness* of the feedback to the user and make sure that they adequately understand the relationships between the biosignal (e.g., cardiac activity) and the addressed constructs that are directly (e.g., arousal, stress) or indirectly (e.g., social interaction, user experience) linked to physiological. For instance, Mueller et al.'s (2010) and Slovák et al.'s (2012) research on foreign live biofeedback shows that heart rate measurements can increase feelings of co-presence and social connectedness. In other contexts, however, heart rate and heart rate variability measurements can help users train their emotion-regulation and stress-management capabilities (Al Osman et al., 2013, 2016; Al Rihawi et al., 2014). One needs to carefully consider the meaning of a particular physiological feature and evaluate it against the background of the study. After all, physiological data are "only meaningful and useful when the user has the ability to understand what is being represented" (Snyder et al., 2015, p. 152).

10.3 Concluding Note

With the advances in mobile sensor technology, researchers and practitioners have begun to explore the integration of neuro-adaptive system components for consumer applications. As a specific category of such systems, live biofeedback systems have emerged in application domains such as gaming, communication, and stress management. Building on the transmission model of communication, we introduce a structured classification of the components and transmission signals in different settings, synthesize a body of highly fragmented literature on self and foreign live biofeedback, and review the measurement tools, user interfaces, and theories to address psychological constructs used in both areas. Furthermore, we identify a set of practical design considerations and important directions for future research on live biofeedback systems for everyday use. We hope that researchers and practitioners will find this review useful as a reference guide to inform the integration of live biofeedback into information systems.

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Appendix: Literature Summary Tables

Table A1. Studies on Self Live Biofeedback

No.	Authors (Year)	Outlet (subject area, domain)	Brief description	Focus variable	Modality / measure-ment	Manifesta-tion
1	Goldstein et al. (1977)	*Biofeedback and Self-Regulation* (Psyc, wellbeing)	Heart rate biofeedback during treadmill exercise	Physiology	ECG	Visual
2	Reynolds (1984)	*Biofeedback and Self-Regulation* (Psyc, wellbeing)	Supporting homeostasis for coping with stress	Stress management	EMG	Auditory
3	Zeier (1984)	*Biofeedback and Self-Regulation* (Psyc, wellbeing)	Arousal reduction with meditation supported by respiratory feedback	Stress management	Resp.	Auditory
4	Chandler et al. (2001)	*Applied Psychophysiology and Biofeedback* (Psyc, wellbeing)	Relaxation training for counselor trainees	Stress management	Temp.	Auditory
5	Lehrer et al. (2003)	*Psychosomatic Medicine* (MS, wellbeing)	Biofeedback for increasing vagal baroreflex gain and improving pulmonary function	Physiology	ECG	Visual
6	Höysniemi et al. (2004)	Nordic Conference on Human-Computer Interaction (CS, games)	Physically interactive fitness game	Physiology	Video	Visual
7	IJsselsteijn et al. (2004)	International Conference on Entertainment Computing (CS, wellbeing)	Virtual coach based on heart rate	User experience	ECG	Visual
8	Davis et al. (2005)	International Conference on Multimedia (CS, art)	Artwork that incorporates heart-rate and GPS data to create a novel user experience	User experience	ECG, GPS	Auditory, visual
9	Rani et al. (2005)	International Conference on Human-Computer Interaction (CS, games)	Maintaining optimal challenge in computer games	Emotion regulation	ECG, EDA, EMG, PPG	Visual
10	Masuko & Hoshino (2006)	International Conference in Advances in Computer Entertainment (CS, games)	A fitness game reflecting heart rate	Physiology	ECG	Visual
11	Buttussi et al. (2007)	*Lecture Notes in Computer Science* (CS, games)	Fitness game that incorporates physiological sensors	User experience	Accel., ECG, PPG	Game mechanics, visual
12	Dekker & Champion (2007)	DiGRA International Conference (CS, games)	Horror game that incorporates physiological data to enhance gameplay	User experience	EDA, PPG	Auditory, game mechanics, visual
13	Friedman et al. (2007)	International Conference on Affective Computing and Intelligent Interaction (CS, art)	Artistic exhibition with skin conductance based navigation through a virtual reality	Navigation	EDA	Visual

Table A1. Studies on Self Live Biofeedback

14	Nenonen et al. (2007)	Conference on Human Factors in Computing Systems (CS, games)	Real-time heart rate data to control a physically interactive biathlon game	User experience	ECG	Game mechanics, visual
15	Oertel et al. (2007)	International Conference on Foundations of Augmented Cognition (CS, education)	E-learning system that aims at supporting an optimum emotional level for learning	Emotion regulation	ECG, EDA, temp.	Changes of learning path, visual
16	Pastor et al. (2008)	*Applied Psychology and Biofeedback* (Psyc, wellbeing)	Skin conductance biofeedback during respiration exercise to reduce arousal	Physiology	EDA	Visual
17	Ebben et al. (2009)	*Applied Psychology and Biofeedback* (Psyc, wellbeing)	Improving sleep quality with biofeedback	Stress management	PPG	Visual
18	Liu et al. (2009)	International Conference of Human-Computer Interaction (CS, games)	Dynamic difficulty adjustment in computer games	Emotion regulation	ECG, EDA, EMG, PPG	Game mechanics, visual
19	Schnädelbach et al. (2010)	Nordic Conference on Human-Computer Interaction (CS, architecture)	Externalizing a person's physiological data using the fabric of building architecture	Adaptive architecture	ECG, EDA, resp.	Auditory, tactile, visual
20	Cederholm et al. (2011)	DiGRA International Conference (IS, economic decision making)	Emotion regulation training with a serious aiming game for financial investors	Emotion regulation	EDA, EEG	Game mechanics, visual
21	Marshall et al. (2011)	Conference on Human Factors in Computing Systems (CS, games)	Breath control of a bucking bronco ride	User experience	Resp.	Game mechanics, visual
22	Moraveji (2011)	ACM Symposium on User Interface Software Technology (CS, wellbeing)	Influencing respiration of a desktop user by integrating respiration-pacing techniques	Stress management	Resp.	Visual
23	Morie et al. (2011)	International Conference on Human-Computer Interaction (IS, wellbeing)	Virtual world application which uses controlled breathing to mitigate stress	Stress management	Resp.	Auditory, visual
24	Nacke et al. (2011)	Conference on Human Factors in Computing Systems (CS, games)	Enhancing game interaction by means of direct and indirect physiological control	User experience	ECG, EDA, EMG, eye tracking, PPG, resp., temp.	Game mechanics, visual
25	Tennent et al. (2011)	International Conference on Entertainment Computing (CS, games)	Breath control as an interaction medium for gaming	User experience	Resp.	Game mechanics, visual
26	Bouchard et al. (2012)	*PLoS ONE* (Psyc, wellbeing)	Stress management training for soldiers	Stress management	ECG, EDA	Auditory, visual
27	Jercic et al. (2012)	European Conference on Information Systems (IS, economic decision making)	Serious game for emotion regulation training in financial decision making	Emotion regulation	ECG	Auditory, visual

Table A1. Studies on Self Live Biofeedback

28	Reitz et al. (2012)	International Conference on Human-Computer Interaction with Mobile Devices and Services (CS, games)	Personalized gaming experience by integrating biofeedback into gameplay	User experience	ECG, EDA	Game mechanics, visual
29	Schnädelbach et al. (2012)	*ACM Transactions on Computer-Human Interaction* (CS, architecture)	Physiologically Driven Adaptive Architecture	Adaptive architecture	ECG, EDA, resp.	Auditory, tactile, visual
30	Vidyarthi et al. (2012)	Designing Interactive Systems Conference (CS, wellbeing)	Fostering of meditation by connecting respiration to music	Stress management	Resp.	Auditory
31	Al Osman et al. (2013)	*Multimedia Tools and Applications* (CS, wellbeing)	Stress management application for office workers	Stress management	ECG, resp.	Visual
32	Astor et al. (2013)	*Journal of Management Information Systems* (IS, economic decision making)	Serious game for emotion regulation training in financial decision making	Emotion regulation	ECG	Visual
33	Feijs et al. (2013)	International Conference of Design, User Experience, and Usability (CS, wellbeing)	Biofeedback to enhance relaxation during milk expression	Stress management	EDA	Auditory, visual
34	Hilborn et al. (2013)	International Conference on Human-Computer Interaction (IS, games)	Biofeedback game for training arousal regulation during a stressful task	Emotion regulation	ECG	Visual
35	Horta et al. (2013)	IEEE International Conference on e-Health Networking, Applications and Services (MS, wellbeing)	Biofeedback monitoring solution for real-time falls prevention and detection	Health	Accel., ECG, EDA, EMG, PPG, resp.	Visual
36	MacLean et al. (2013)	International Conference on Pervasive Technologies Related to Assistive Environments (ET, wellbeing)	Wearable biofeedback device to mirror a user's real-time stress state	Stress management	EDA	Visual
37	Sakakibara et al. (2013)	*Applied Psychology and Biofeedback* (Psyc, wellbeing)	Use of HRV biofeedback to improve the cardiorespiratory resting function during sleep	Stress management	PPG	Visual
38	Xiong et al. (2013)	International Conference on Smart Health (MS, wellbeing)	Biofeedback system for mobile healthcare based on heart rate variability	Physiology	ECG, resp.	Visual
39	Al Rihawi et al. (2014)	Conference on Human Factors in Computing Systems (CS, wellbeing)	Personalized biofeedback game to train subjects to relax during gameplay	Stress management	Resp.	Visual
40	Chittaro & Sioni (2014)	*International Journal of Human-Computer Studies* (IS, wellbeing)	Biofeedback-controlled game for relaxation training	Stress management	EDA, EMG, PPG	Auditory, visual
41	Hicks et al. (2014)	Effective Access Technology Conference (ET, wellbeing)	Using peripheral biofeedback to facilitate autonomic regulation	Emotion regulation	EDA, PPG, resp., temp.	Visual

Table A1. Studies on Self Live Biofeedback

42	Peira et al. (2014)	*International Journal of Psychophysiology* (Psyc, wellbeing)	Use of HR biofeedback to improve cardiac control during emotional reactions	Emotion regulation	ECG	Visual
43	Chollet et al. (2015)	International Joint Conference on Pervasive Ubiquitous Computing (CS, education)	Interactive virtual audience platform for public speaking training	Speech	Video	Visual
44	Matthews et al. (2015)	Conference on Human Factors in Computing Systems (CS, well-being)	Playful biofeedback system that uses ambient colored light for stress management	Stress management	EDA	Visual
45	Meier and Welch (2016)	*Anxiety, Stress, & Coping* (Psyc, wellbeing)	Paced breathing exercise for college students to manage stress	Stress Management	Resp.	Visual
46	Millings et al. (2015)	*Internet Inventions* (MS, wellbeing)	Incorporation of wearable sensor biofeedback into a stress management program to improve mental health among students	Stress management	ECG	Visual
47	Ueoka & Ishigaki (2015)	International Conference on Human-Computer Interaction (IS, games)	Cross modal display system to enhance horror emotion	Physiology	PPG	Tactile
48	Al Osman et al. (2016)	*IEEE Access* (CS, wellbeing)	Stress management through a serious game	Stress management	Accel., ECG, resp.	Visual
49	Dillon et al. (2016)	Conference on Human Factors in Computing Systems (Psyc, wellbeing)	Smartphone application to reduce physiological markers of stress in young adults	Stress management	EDA	Auditory, game mechanics, visual
50	Li et al. (2016)	International Conference of the Engineering in Medicine and Biology Society (MS, sports)	Wearable feedback to improve swimmers kinematic performance	Physiology	Accel.	Tactile
51	McGregor et al. (2016)	*Journal of Sports Engineering and Technology* (ET, sports)	Support of rowing training through feedback on body segment motion	Physiology	Accel.	Visual
52	Munafo et al. (2016)	*Applied Psychology and Biofeedback* (Psyc, wellbeing)	Respiratory Sinus Arrhythmia biofeedback for improving manager's well-being	Stress management	PPG, resp.	Visual
53	Perera et al. (2016)	International Conference on Advances in ICT for Emerging Regions (CS, wellbeing)	Biofeedback assisted mindfulness meditation for stress reduction	Stress management	EDA	Visual
54	Rijken et al. (2016)	*Applied Psychology and Biofeedback* (CS, wellbeing)	Peak performance training for athletes	Stress management	ECG, EEG	Auditory, visual
55	Vieira et al. (2016)	*Frontiers in Physiology* (Psyc, wellbeing)	Minimization of calf muscle activation during standing	Physiology	EMG	Auditory

Note: Accel.: acceleration; ECG: electrocardiography; EDA: electrodermal activity; EEG: electroence-phalography; EMG: electromyography; GPS: global positioning system; PPG: photoplethysmography; resp.: respiration; temp. = temperature; CS: computer science; ET: engineering & technology; IS: information systems; MS: medical science; Psyc: psychology; #P: number of study participants. We categorize outlets into subject areas based on the ABS Academic Journal Guide 2015 and SCImago Journal and Country Rank. The table lists the studies in chronological order.

Table A2. Studies on Foreign Live Biofeedback

No.	Authors (Year)	Outlet (subject area, domain)	Brief description	Focus variable	Modality / measure-ment	Manifesta-tion
56	Picard & Scheirer (2001)	International Conference on Human-Computer Interaction (CS, interpersonal communication)	LED display based on skin conductivity for communication (self-to-self, foreign-to-self, self-to-foreign)	Social interaction	EDA	Visual
57	Al Mahmud et al. (2007)	Conference on Interaction Design and Children (CS, games)	Social gaming application for children (foreign-to-self, self-to-foreign)	User experience	ECG, EDA	Visual
58	de Oliveira & Oliver (2008)	International Conference on Human-Computer Interaction with Mobile Devices and Services (CS, sports)	Fitness game that increases personal awareness and facilitates virtual competition (self-to-self, foreign-to-self, self-to-foreign)	User experience	ECG, Accel.	Visual
59	Magielse & Markopoulos (2009)	Conference on Human Factors in Computing Systems (CS, games)	Outdoor game for children incorporating physiological data (self-to-self, foreign-to-self, self-to-foreign)	User experience	ECG, Accel.	Auditory
60	Stach et al. (2009)	Graphics Interface (CS, games)	Multiplayer fitness game with heart rate based game control (self-to-self, foreign-to-self, self-to-foreign)	User experience	ECG	Visual
61	Mueller et al. (2010)	*ACM Symposium on User Interface Software and Technology* (CS, sports)	Social exertion experience with a heart-rate based spatialized audio system (self-to-self, foreign-to-self, self-to-foreign)	Social interaction	ECG	Auditory
62	Slovák et al. (2012)	Conference on Human Factors in Computing Systems (CS, interpersonal communication)	Heart rate communication to improve social connectedness (self-to-self, foreign-to-self, self-to-foreign)	Social interaction	ECG	Auditory, visual
63	Curmi et al. (2013)	Conference on Human Factors in Computing Systems (CS, social media)	Broadcasting heart rate data to social networks (foreign-to-self)	Social interaction	ECG, GPS	Tactile, visual
64	Fernández et al. (2013)	*Journal of Universal Computer Science* (CS, economic decision making)	Self-aware trader system to help traders to reach safer financial decisions using biofeedback (self-to-self, foreign-to-self, self-to-foreign)	Stress management	PPG	Visual
65	Mueller & Walmink (2013)	Australasian Conference on Interactive Entertainment (CS, games)	Engaging gameplay in a sword fighting game with real-time body data (foreign-to-self, self-to-foreign)	User experience	PPG	Visual
66	Walmink et al. (2013)	International Conference on Tangible, Embedded and Embodied Interactions (CS, sports)	Display of heart rate data on a bicycle helmet to support social exertion experiences (foreign-to-self, self-to-foreign)	Social interaction	PPG	Visual

Table A2. Studies on Foreign Live Biofeedback

67	Tan et al. (2014)	Conference on Human Factors in Computing Systems (CS, interpersonal communication)	Biofeedback to reduce stress and workload during video-mediated collaboration (self-to-foreign)	Stress management	EDA, PPG, resp.	Visual
68	Huang & Luk (2015)	International Conference on Human-Computer Interaction (CS, games)	Biofeedback board game to improve coordination and emotional control (self-to-self, foreign-to-self, self-to-foreign)	Stress management	ECG	Game mechanics, tactile, visual
69	Roseway et al. (2015)	*International Journal of Mobile Human Computer Interaction* (CS, wellbeing)	Colored crystal based on physiology for increasing awareness and mood sharing (self-to-self, foreign-to-self, self-to-foreign)	Social interaction	ECG, EDA	Visual
70	Snyder et al. (2015)	ACM Conference on Computer Supported Cooperative Work & Social Computing (CS, interpersonal communication)	Exploring personal and social implications of ambient display of biosensor data (self-to-self, foreign-to-self, self-to-foreign)	Stress management	EDA	Visual
71	Gervais et al. (2016)	International Conference on Tangible, Embedded and Embodied Interactions (CS, wellbeing)	Toolkit for reflection of physiological and mental states (self-to-self, foreign-to-self, self-to-foreign)	Social interaction	ECG, EDA, EEG, EOG, resp.	Visual
72	Howell et al. (2016)	Designing Interactive Systems Conference (CS, interpersonal communication)	T-shirt that indicates changes in skin conductance (self-to-self, foreign-to-self, self-to-foreign)	Social interaction	EDA	Visual
73	Järvelä et al. (2016)	*Frontiers in Psychology* (Psyc, interpersonal communication)	Display of physiological linkage based on HR synchrony (self-to-self, foreign-to-self, self-to-foreign)	Social interaction	ECG	Visual
74	Moran et al. (2016)	International Joint Conference on Pervasive Ubiquitous Computing (CS, wellbeing)	Actuated environment for supporting yoga breathing practices (self-to-self, foreign-to-self, self-to-foreign)	Social interaction	Resp.	Visual
75	Muñoz et al. (2016)	International Conference on Physiological Computing Systems (CS, games)	Multiplayer game to encourage collaboration (self-to-self, foreign-to-self, self-to-foreign)	Social interaction	EEG, resp.	Game mechanics, visual
76	Yu et al. (2016)	International Conference on Tangible, Embedded and Embodied Interactions (CS, art)	Interactive wall surface reflecting the internal bodily processes (self-to-self, foreign-to-self)	User experience	PPG	Visual

Note: ECG: electrocardiography; EDA: electrodermal activity; EEG: electroencephalography; EOG: electrooculography; GPS: global positioning system; PPG: photoplethysmography; Resp.: respiration; CS: Computer science, Psyc: Psychology; #P: number of study participants. We categorize outlets into subject areas based on the ABS Academic Journal Guide 2015 and SCImago Journal and Country Rank. The table lists the studies in chronological order.

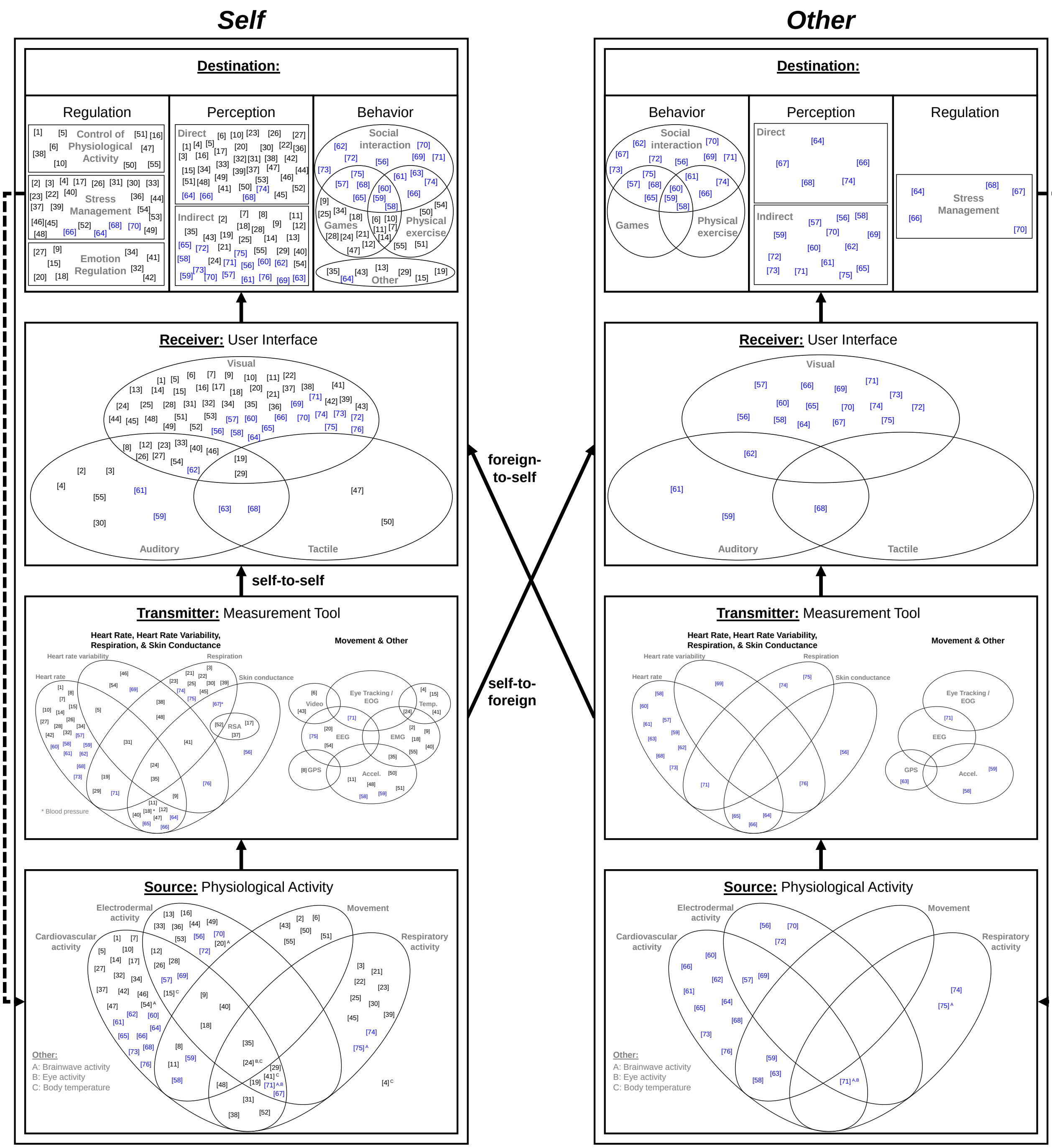

Figure A1. Mapping of the Reviewed Self and Foreign Live Biofeedback Studies to the Integrative Framework for Live Biofeedback[11]

[11] Each number represents one of the 76 studies covered in the review (they correspond to the studies that Tables A1 and A2 list). The figure indicates self live biofeedback studies in black and foreign live biofeedback studies in blue. Accel.: acceleration; EEG: electroencephalography; EOG: electrooculography; the terms "self-to-self", "self-to-foreign", and "foreign-to-self" indicate the three types of transmission signals.

About the Authors

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