BIOFEEDBACK SYSTEMS FOR STRESS REDUCTION
Towards a Bright Future for a Revitalized Field

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Abstract: Stress has recently been baptized as the black death of the 21st century, which illustrates its threat to current health standards. This article proposes biofeedback systems as a means to reduce stress. A concise state-of-the-art introduction on biofeedback systems is given. The field of mental health informatics is introduced. A compact state-of-the-art introduction on stress (reduction) is provided. A pragmatic solution for the pressing societal problem of illness due to chronic stress is provided in terms of closed loop biofeedback systems. A concise set of such biofeedback systems for stress reduction is presented. We end with the identification of several development phases and ethical concerns.

1 INTRODUCTION

Throughout its existence, biofeedback has been criticized almost continuously (Moss and Gunkelman, 2002; Moss et al., 2004). The latest boost of criticism and a response on it dates from around the change of the century. Amongst many other issues of criticism, the lack of proven efficacy, the absence of standards, and the fuzzy relation between biosignals and psychological constructs were mentioned. Therefore, to establish a solid ground for the current article, we will define the core concepts (i.e., biosignals and biofeedback) at hand and denote their relations.

Physiological or biosignals can be conceptualized as (bio)electrical signals recorded on the surface of the body. These bio(electrical) signals are related to ionic transport that arises as a result of electrochemical activity of cells in specialized tissue (e.g., the nervous system), so-called autonomic responses. This results in (changes in) electric currents produced by the sum of electrical potential differences across the tissue. This process is the same regardless of where in the body the cells are located (e.g., the heart, muscles, skin, or the brain) (Sörnmo and Laguna, 2005). So, biosignals reflect the physiological activity of a person. This latter definition also includes both non-electrical biosignals, such as skin temperature, and signals obtained through invasive recording techniques.

Biosignals are employed to enable biofeedback, as the name already reveals. On May 18, 2008, the Association for Applied Psychophysiology and Biofeedback (AAPB), the Biofeedback Certification International Alliance (BCIA), and the International Society for Neurofeedback and Research (ISNR)[1] jointly agreed on a standard definition of biofeedback:

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.

[1]For more information, see: http://www.aapb.org/, http://www.bcia.org/, and http://www.isnr.org/.

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This was one of the results of a joint task force, initiated by the AAPB and the ISNR in 2001 (Moss and Gunkelman, 2002; Moss et al., 2004). Other results included a series of white papers and a review of the clinical efficacy of biofeedback (Moss et al., 2004). The definitions of both biosignals and biofeedback provide the premises for this article. To also understand the criticism biofeedback has been subjected to, we need to go back in time, to the invention of biofeedback, and put the work on biofeedback into historical perspective.

The origin of biofeedback takes us back to 1932, the year in which Johannes Heinrich Schultz (1884 – 1970) published a book on a relaxation technique he baptized autogenic training. In 2003, the twentieth edition of this book was published, which marks its continuing influence (Schultz, 2003). However, Schultz did not provide direct biofeedback, his technique relies on introspection, and no signals are fed back to the user. It took more than 25 years until biofeedback, as has just been defined, was reported (Mandler et al., 1958). They referred to it as autonomic feedback, which they defined as: *the relationship between autonomic response and the subject's reported perception of such response-induced stimulation* (Mandler et al., 1958, p. 367).

The work of (Mandler et al., 1958) was conducted more than half a century ago, in the early years of computing machinery. At that time, computers were invented for highly trained operators, to help them do massive numbers of calculations (Sifakis, 2011). However, much has changed since then; nowadays, everybody uses them in one of their many guises. Today we are in touch with various types of computers throughout our normal daily lives, including our smartphones (Agrawal, 2011). Computation is on track to become even smaller and more pervasive. Not only computing machinery miniaturized, biomedical apparatus has also done so (Ouwerkerk et al., 2008). Consequently, biosignals (or physiological signals) still receive increasing interest as an interface between users and their computing devices. It is envisioned that computers will become a window to the world as a whole, to our social life, and even to ourselves (Davies, 2011).

Computers are slowly becoming dressed, huggable, and tangible. Concepts such as stress and emotions, which were originally the playing field of philosophers, sociologists, and psychologists (Izard et al., 2010), have already become entangled in computers (and in computer science) as well. With this, it has become much easier for us than before to accept biosignals as relevant reflections of our lives, and biofeedback as a means to alter them. Also biofeedback standards can emerge more easily with ICT help. Thus two of the traditional criticisms of biofeedback are on the verge of being tackled. And while the embedding of biofeedback into psychological constructs remains unclear, the first efficacy evaluations of biofeedback have started to prove its usefulness (Gruzelier et al., 2006).

In the next section, we will provide a concise introduction on mental health informatics, as opposed to general (physical) health informatics, with an emphasis on (chronic) stress. In Section 3, we will provide a concise overview of our working model for stress reduction: a closed loop biofeedback model. Last, in Section 4, we will provide a general discussion.

2 MENTAL HEALTH INFORMATICS AND STRESS (REDUCTION)

In 1935, Flanders Dunbar noted that the "*Scientific study of emotion and of the bodily changes that accompany diverse emotional experiences marks a new era in medicine*" (Dunbar, 1954, p. vii). We know now that many physiological processes that are of profound significance for health can be influenced by way of emotions (Kaklauskas et al., 2011). For example, it has been shown that emotions influence our cardiovascular system and, consequently, can shorten or prolong life (Lucas et al., 2009). Moreover, chronic stress also plays an important role with chronic diseases (Berg and Upchurch, 2007), cancer (e.g., coping strategies) (Taylor and Stanton, 2007), and rehabilitation (Novak et al., 2010), to mention three.

Flanders Dunbar drew the conclusion: "*In this knowledge, we have the key to many problems in the prevention and treatment of illness, yet we are scarcely begun to use what we know. We lack perspective, concerning our knowledge in this field, and are confused in our concepts of the interrelationship of psychic, including emotional, and somatic processes in health and disease.*" (Dunbar, 1954, p. vii). Nevertheless, emotions remained rather spiritual and human's health has usually been explained in physical (e.g., injuries) and physiological terms (e.g., bacteria and viruses). The field of biofeedback also suffered severely from this attitude. It is only since the last decades that it has generally been acknowledged that emotions have their impact on health and illness (Kaklauskas et al., 2011).

Now emotions have been acknowledged by traditional medicine, stress is being given a position in health informatics. This shift was accelerated by the general increase in the need for health informatics that has emerged due to the massive growth of the market for new systems that improve productivity, cut costs, and support the transition of health care from hospital to the home (Dumaij and Tijssen, 2011). Health informatics is already or will soon be applied for the support/assistance of independent living, chronic disease management, facilitation of social support, and to bring the doctor's office to people's homes. Par excellence, this is where informatics and *mental health care* blend together.

Recently, stress has been baptized as being the black death of the 21st century. Although this is a very bold statement, it illustrates that (chronic) stress is an important threat to modern societies, both in terms of severity and in terms of proportion. As such, it is now receiving top priority in health care and is the #1 priority in mental health care.

Humans can make cognitive representations of events, from the past as well as for the future. This ability distinguishes them from (most) animals. These representations aid our daily work and living; however, they also have their down side. In stressful life events, cognitive representations can facilitate worrying and, consequently, catalyze chronic stress, which is unknown to animal species (Brosschot, 2010).

When stress is experienced, often similar physiological responses emerge as during the stressful events from which it originates: the repetition of such physiological responses can cause pervasive and structural chemical imbalances in people's physiological systems, including their autonomic and central nervous system, their neuroendocrine system, their immune system, and even in their brain (Brosschot, 2010). A thorough understanding of stress is still missing. This can be explained by the complexity of human's physiological systems, their continuous interaction, and their integral dynamic nature.

Current day treatments of stress focuses on the treatment of either cognitive representations, our (unconscious) habit memory system, or both (Schwabe et al., 2010). In general, under stressful events, the habit memory system tends to dominate over the cognitive memory (or representations) system; however, their precise relation remains unknown (Schwabe et al., 2010). This lack of understanding makes treatment inherently complex and requires a very high level of expertise from the clinician. Moreover, most indicators of the patients' progress rely on behavior measures and the clinician's expertise.

A possible alternative for the clinician's expertise is the use of biofeedback systems for stress reduction. On the one hand, these systems have the obvious

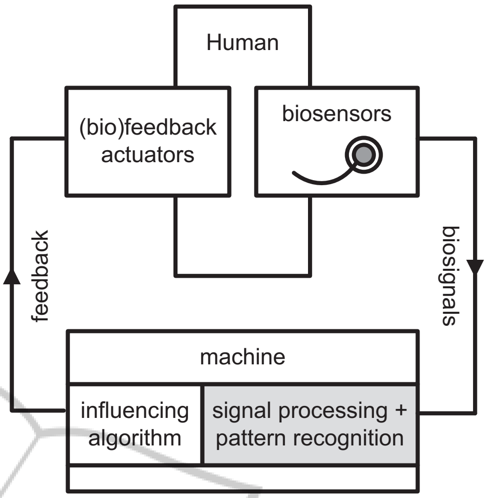

Figure 1: The (general) biofeedback closed loop model. For details on the model's signal processing + pattern recognition component, we refer to (van den Broek et al., 2010). Within the scope of this article, the model's domain of application is mental health care, in particular stress reduction.

disadvantages that they can be obtrusive, can process only a few or even a single signal, and their means to interact with their user are severely limited as well. On the other hand, biofeedback systems are becoming reliable and robust, affordable, and can be applied when and where ever needed or appreciated (without any additional costs). Moreover, biofeedback systems for stress reduction enable an anonymous treatment and can be (automatically) personalized. These two aspects could be potential strengths of such systems but could also turn out to be their weaknesses.

Taken together, both the pros and cons of biofeedback systems for stress reduction are strong. Moreover, stress is a complex phenomenon, which is far from completely unraveled. Hence, these limitations need to be respected and the claims surrounding them should be chosen with care. For example, given the current state of the art of science and engineering, biofeedback systems for stress reduction might only be employed successfully with people who do not yet suffer severely (or already for a vast amount of time) from stress. However, even then, biofeedback systems for stress reduction can still be useful for a large portion and for a still increasing part of the population.

3 THE CLOSED LOOP

To enable autonomous biofeedback systems, a closed loop model has to be adopted, incorporating both measurement and feedback components. Such a model can, but does not necessarily involve the intervention of a therapist. Consequently, (closed loop) biofeedback systems can be positioned in the large market of health care-related consumer electronics.

For over a century, closed loop models have been known in science and engineering, in particular in control theory and electronics (Neamen, 2010). Closed loop models can be defined as control systems with an active feedback loop. This loop allows the control unit to dynamically compensate for deviations in the system.

The output of the system is fed back through a sensor measurement to a control unit, which takes the error between a reference and the output to change the inputs to the system under control.

A relatively new class of closed loop models are biofeedback systems: closed loops that take a human into the loop; see also Figure 1. The descriptions of these biofeedback systems target various areas but are essentially the same, comprising: sensors, processing, influencing algorithm (feedback decision), and actuators. In essence, biofeedback systems for stress reduction are described by four basic steps:

1. **Sensing.** Data collection starts at the sensors, where a raw signal is generated that contains an indication of a person's mental state, e.g. his stress level. Relevant signals can include both overt and covert bodily signals, such as facial camera recordings, movements, speech samples, and biosignals.
2. **Signal Processing + Pattern Recognition.** Exploiting signal features that could contain stress level information; for example, the number of peaks in the ElectroDermal Activity (EDA) signal can be counted, serving as a measure for stress. For more information on this step, we refer to (van den Broek et al., 2010).
3. **Influencing Algorithm.** Given the obtained affective state of the user, a decision is made as to what feedback to provide to the user. Next, we will provide various examples of this.
4. **Feedback Actuators.** The feedback is provided by a set of actuators. Such actuators can directly communicate with our body, either physically (Hatzfeld et al., 2010) or chemically (Mielle et al., 2010). Alternatively, actuators can communicate indirectly and influence our environment as we sense it either consciously or unconsciously; for instance, a song can be played or lighting can be activated to create a certain ambiance. The optimal way to present this feedback information is part of the field of Human-Computer Interaction.

The loop (always) closes with a new measurement of the sensors, which is again evaluated as to whether or not the intended level of stress has indeed been reached. If the intended level of stress has indeed been reached, the system will perform no further action. Thus the system guides the user towards a certain state. Also in the field of Brain-Computer Interaction (BCI) closed loops play an important role (van Gerven et al., 2009). For traditional BCI devices (e.g., those allowing locked-in patients to communicate), however, there is no target state included in a feedback algorithm, but instead it is the user who guides the system to a certain state.

The feedback is determined by biosignals but is most often of another modality itself. With the vast progress of informatics, omnipresent computing (also known as Ambient Intelligence (AmI), Ubiquitous Computing (UbiComp), the Internet of Things, and the World Wide Wisdom Web (W4) (Friedewald and Raabe, 2011) are about to enter our lives. This provides a seemingly infinite number of possibilities to provide the (bio)feedback. We will mention three of them:

1. **(Ambient) Lighting:** (i) The color of light can be altered to provide the experience of another color to people, which can either activate or relax them (Küller et al., 2009) and (ii) The Rationalizer concept: an EDA-based emotion sensing wristband that offers stress level feedback to stock traders, using a LED bowl (Ouwerkerk, 2011).
2. **Audio and Video:** (i) The RelaxTV concept uses a biosensor to monitor the relaxation of a person. Biofeedback techniques were developed to use breathing guidance for deep relaxation of a television viewer (Ouwerkerk, 2011) and (ii) A personalized affective music player to augment music experience and direct the listener's mood (Janssen et al., 2012), for instance to a relaxed state.
3. **Tactile Feedback:** (i) Research is conducted with tactile sensation as emotion elicitor, by means of an augmented PC mouse, which can be conveniently used in the context of work occupational stress (Suk et al., 2009) and (ii) (Plasier, 2011) introduced an electronic singing bowl. Traditional Tibetan versions of these bowls are used to provide relaxing body vibrations along with the sounds.

This triplet illustrates the latest developments on biofeedback. However, many more have been proposed and even more yet are currently being investigated. It can be expected that the field will mature further and the systems will become robust. Then, within 10 years from now, consumers can buy such biofeedback systems in their electronics stores.

4 DISCUSSION

This article proposed biofeedback systems as a means to reduce stress, which is becoming a pregnant issue in our modern society. First, the necessary basic information was provided in terms of a definition and a sketch of the origin of biofeedback systems. Next, the field of mental health informatics was introduced followed by the article's topic: stress (reduction). (Closed loop) biofeedback systems were introduced as a feasible solution for the pressing societal problem of illness due to chronic stress. Moreover, several examples of biofeedback systems for stress reduction were provided.

Traditionally, research towards biofeedback systems has been approached from a range of sciences (e.g., psychology, medicine, and computer science) and often the research explores the feasibility of such systems and has not yet actually implemented them. However, the closed-loop model allows us to identify the three main phases of (subsequent) development:

1. Computational modeling founded on theory, without experimental validation. Such systems have been proposed by themselves; however, in the perspective of biofeedback systems, such models can be considered as the very first phase of the actual development.
2. Stress elicitation and measurement, with or without classification component. This type of research is conducted in three environments (Healey, 2008): *i*) controlled laboratory research; *ii*) semi-controlled research (e.g., as in smart homes); and *iii*) ambulatory research.
3. Development of the actual biofeedback systems, in which one can distinguish: *i*) the initial off-line modeling and *ii*) online, real-time modeling.

This division is not as strict as it may appear; often mixtures of these three phases of development are employed and iterations and loops are applied. Nevertheless, it should be noted that, so far, a vast amount of research on applied biofeedback for stress reduction has not implemented the required closed loop model (Janssen et al., 2012). Instead most studies present either theoretical computational modeling or solely stress elicitation and measurement. Moreover, most research has been conducted in (semi-) controlled settings. And even though ambulatory research with loose constraints, conducted in the real world, is still relatively rare (Healey, 2008) (cq. (Janssen et al., 2012)), we do expect a rise of closed loop biofeedback systems for stress reduction.

Building biofeedback systems for stress reduction is a process in which law and ethics will claim their place too (Floridi, 2010). Law considerations comprise: *i*) rules of privacy, *ii*) the constitutional background, and *iii*) privacy under law, including physical, decisional, and information privacy. Ethical considerations emerge from the notion that biofeedback systems would extend the scope of traditional information collection. One of the ethical issues is that biofeedback systems may introduce the risk of social exclusion for those who do use them, or maybe even for those who do not. This makes the balance between intelligence (e.g., AmI) and privacy even more sensitive than, for example, with biometrics. Taken together, perhaps more than anything else, human dignity should be a leading denominator in future research on biofeedback systems for stress reduction (Coeckelbergh, 2011).

Stress is heading to become the #1 in (chronic) diseases. As such its societal impact is enormous. With this article we hope to bring the need for a solution to the attention of the health informatics society. Closed loop biofeedback systems for stress reduction are proposed as a feasible solution and examples of such systems have been described. Taken together, we propose to increase the efforts towards biofeedback systems for stress reduction, if not for the sake of science then at least for the sake of society.

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