A closed-loop Brain-Computer Music Interface for continuous affective interaction

Stefan Ehrlich
Chair for Cognitive Systems
Technische Universität München
München, Germany
Email: stefan.ehrlich@tum.de

Cuntai Guan
School of Computer Science and Engineering
Nanyang Technological University
Singapore
Email: ctguan@ntu.edu.sg

Gordon Cheng
Chair for Cognitive Systems
Technische Universität München
München, Germany
Email: gordon@tum.de

***Abstract*—Research on human emotions and underlying brain processes is mostly performed *open-loop*, e.g. by presenting emotional stimuli and measuring subject's brain responses. Investigating human emotions in interaction with emotional stimuli (closed-loop) significantly complicates experimental setups and has so far rarely been proposed. We present concept and technical realization of an electroencephalography (EEG)-based affective Brain-Computer Interface (BCI) to study emotional brain processes *in continuous closed-loop interaction*. Our BCI consists of an algorithm generating continuous patterns of synthesized affective music, embedded in an online BCI architecture. An initial calibration is employed to obtain user-specific models associating EEG patterns with affective content in musical patterns. These models are then used in online application to translate the user's affect into a continuous musical representation; playback to the user results in closed-loop affective brain-interactions. The proposed BCI provides a platform to stimulate the brain in a closed-loop fashion, offering novel approaches to study human sensorimotor integration and emotions.**

***Keywords*-Brain-Computer-Interface (BCI), affective BCI, neurofeedback, emotions**

I. Introduction

In emotion research, Damasio's work showed how crucial emotions are to cognitive brain processes [1]. His research suggests that emotions serve the function of an important regulator for higher-order brain mechanisms involved in reasoning and decision making. Moreover, several challenging and hardly manageable mental diseases, such as depression, have their origin in affective dysfunctions [2]. The rise of *Affective Computing* [3] has attracted the technical area to become increasingly interested in the neuroscientific underpinnings of emotions. Hence, a better understanding of human emotions has interdisciplinary impact on many fields, such as technology, healthcare, and human-sciences.

This work presents a novel non-invasive Brain-Computer Interface (BCI) that feedbacks a subject's emotional state in a way such, that closed-loop affective brain interaction is established. This affective interaction forms an alternative way of stimulating the brain and offers novel approaches to gain fundamental knowledge about emotions, related brain processes and dysfunctions in these structures.

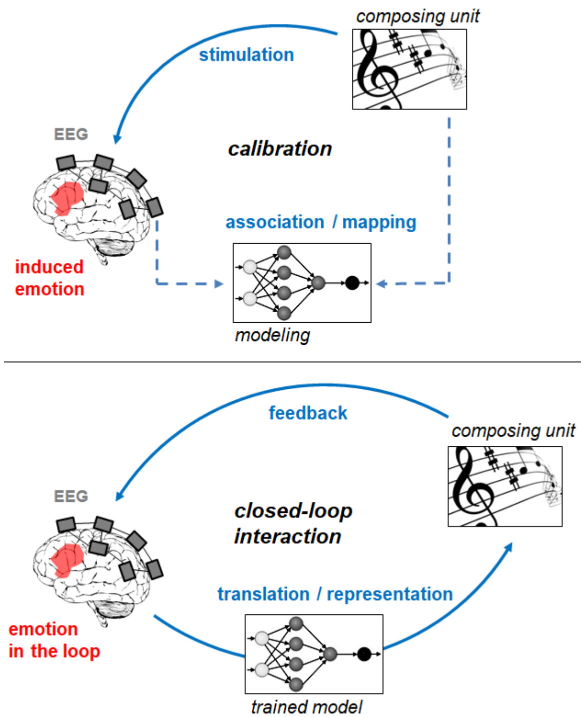

Figure 1. Conceptual illustration of the affective music BCI: During calibration (top) the user is exposed to algorithmically synthesized patterns of affective music; brain activity is measured simultaneously via EEG; EEG patterns are extracted and used to build a user-specific emotion model. During online application (bottom) the obtained model is used to translate the user's brain activity continuously into a musical representation; closing the loop by playing back the musical representation to the user results in continuous affective brain interactions.

The remainder of this paper is structured as follows: In the next section the affective BCI concept and related work will be introduced, followed by the technical realization and evaluation in section III. In section IV we discuss the work and conclude it in section V.

II. Concept and related work

A field, relevant to our concept is commonly referred as *EEG emotion recognition and affective BCI*. It aims for modeling links between neural correlates and emotions to enable a computer device to detect user's affective states by means of recorded EEG signals. A common procedure is exposing subjects to affective stimuli, such as pictures, sound, or music and let them subjectively

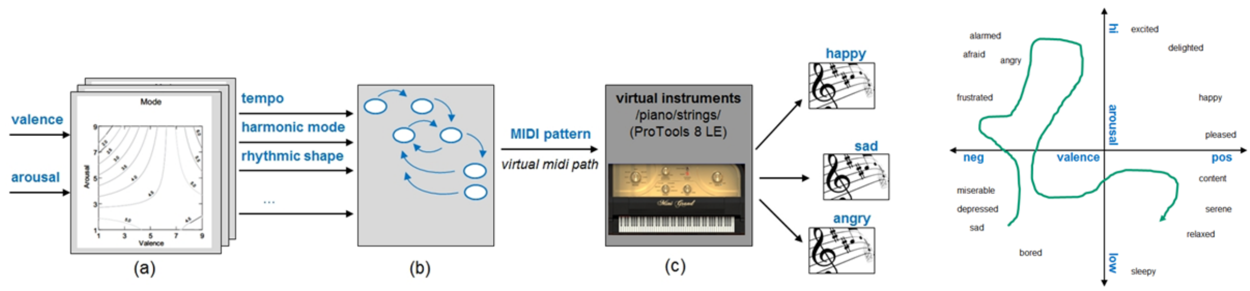

Figure 2. Algorithm to generate continuous patterns of synthesized affective music (composing unit): (a) Mapping of emotion-specific parameters onto music structural control parameters according to results of psycho-physiological studies [6]; (b) state-machine generating streams of MIDI-events, modulated by music structural control parameters; (c) translation of MIDI-patterns into sound. Right: Exemplary musical trajectory through valence-arousal space according to Russel in 1980 [4].

rate their corresponding emotional responses, while brain activity is measured simultaneously. The subjective ratings are later used to identify neural correlates which are subsequently used to build emotion models using statistical modeling [5]. Decoding human affective states is interesting for a multitude of applications, ranging from augmentation of human-computer and human-robot interaction [6], gaming and entertainment, e-learning, as well as in neuro-rehabilitation of psychiatric disorders [7].

A second field relevant to our concept is *EEG sonification and Brain-Computer Music Interfaces*. The basic idea is to translate human brain activity into sound or music. The first premier of a Brain-Computer Music Interface was Alvin Lucier's "Music for Solo Performer" presented in 1965 [8]. More recent works have been presented by Makeig *et al.* in 2011 [9], De Smedt and Menschaert in 2012 [10], and most recently by Deuel *et al.* in 2017 [11]. The majority of these works were focused on artistic purposes, whereby the latter particularly raised the potential use of their system as a biofeedback device.

Our concept: The core component of our concept - and the major contrast to previous works - is the utilization of a single parametrizable music synthesis algorithm (see Figure 1). This algorithm allows for generating musical sequences with seamless and continuous transitions between patterns of different emotional expressiveness. As such it is universally applicable in both, the calibration (EEG-based affect modeling), and the online application phase (continuous EEG-based affect translation). The major benefit is improved calibration-to-application immediacy and transferrablity, but also high flexibility for developing innovative stimulation/calibration protocols.

III. Technical Realization and Evaluation

A. *Algorithm to generate synthesized affective music (composing unit)*

Music can be considered a combination of multiple harmonic, rhythmic and timbre components which change over time and thus form a musical piece. Based on that principle, we designed and implemented an algorithm to generate continuous patterns of affective music whose basic architecture was mainly inspired by Wallis *et al.* in 2011 [12] (for the remainder of this paper this algorithm is called *composing unit*[1]. The composing unit was implemented as a state machine (see Figure 2 (b)) generating streams of MIDI-events. Transitions and states are modulated by several continuously controllable music structural parameters, namely: *harmonic mode*, *tempo*, *rhythmic shape*, *pitch*, and *relative loudness of subsequent notes*. According to their settings, different musical patterns are generated. Emotional expressiveness of these patterns is realized by introducing mappings of emotion related parameters (valence and arousal) onto the music structural parameters (see Figure 2, (a)). As for these mappings, we employed a subset of functional relationships proposed by Gomez and Danuser in 2007 [13]. Most importantly, these parameters and mappings are implemented such that continuous and seamless transitions between musical patterns of different emotional expressiveness can be generated (see Figure 2 (right)).

Evaluation: We conducted a study to evaluate whether subjects rate their emotional reponses according to the valence- and arousal-settings of the composing unit when being exposed to the corresponding generated musical pattern. 11 healthy subjects (age: 26.9$\pm$3.4, 7 males) participated in this study. All subjects were exposed to 13 emotionally different musical patterns (uniformely distributed) generated by the composing unit and asked to rate their emotional responses with the Self-Assessment Manikin (SAM)[2] scheme. The results showed that the subjectively rated emotional response highly correlate (Spearman correlation coeff.: $r = 0.52 \pm 0.23$ for valence and $r = 0.68 \pm 0.19$ for arousal) with the intended emotion to be expressed with the generated musical patterns. This suggested that the synthesized musical patterns generated by the composing unit successfully express the intended emotions. The composing unit was utilized and further evaluated in yet another work by Hagerer *et al.* in 2015 on augmentation of affective speech with synthesized music [14].

[1] For sound examples the reader is referred to the following webpage: http://web.ics.ei.tum.de/~ehrlich/affectiveBCI/index.htm

[2] A questionnaire based on symbols to measure emotional affect; by M. Bradley and P. Lang in 1994

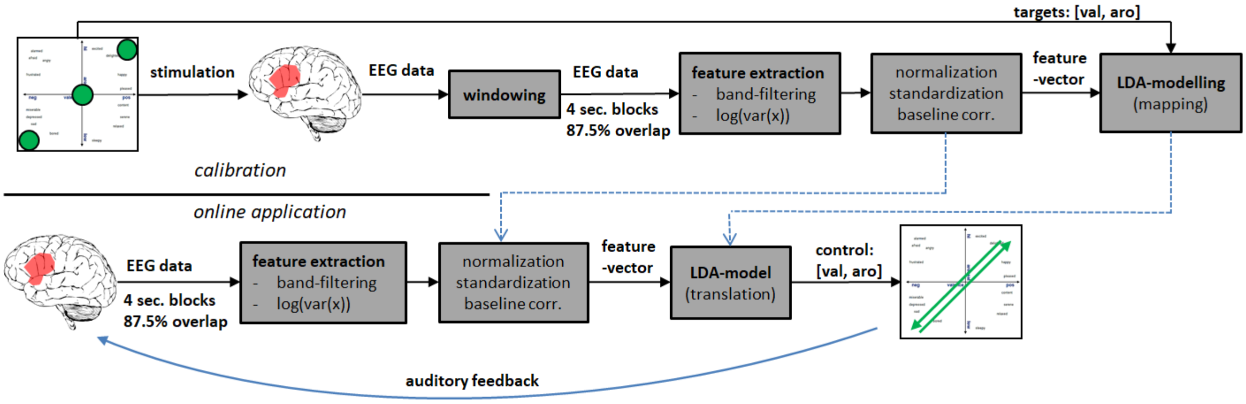

Figure 3. Signal processing and information flow in the affective BCI architecture. Top row (calibration phase): Selected patterns of synthesized affective music are presened to a subject; brain activity is measured simultaneously via EEG and further processed to built a Linear-Discriminant Analysis (LDA) model. Bottom row (application phase): Brain activity is measured and processed according to the training phase; the model output is used to set control parameters (valence, arousal) for the composing unit, resulting in a continuous musical respresentation of the subjects affective state.

B. Affective music BCI: Introducing the composing unit into an online BCI architecture

We embedded the composing unit into an online BCI architecture, consisting of a calibration- and an online application-phase. During the calibration phase (see Figure 1 and 3, top) the subject is exposed to several musical patterns generated by the composing unit, expressing different emotions. Brain activity is measured simultaneously via EEG (14-channel emotiv EPOC system) and afterwards used to build an emotion model: Selected brain activity is mapped onto control parameters for the composing unit by means of statistical modeling (details, see Figure 3). This model is then used during online application to translate the subjects brain activity in real-time into parameter settings for the composing unit (see Figure 1 and 3, bottom). The resulting outcome is a real-time representation of the subjects affective state by means of a music-based emotion display. By playing back this musical representation, the subject's affective state is influenced which again manifests in changes in the musical representation and so on: An affective closed-loop interaction is established.

Evaluation: In a second study, we investigated and quantified the feedback modulations when subjects were interacting with the music feedback. 5 healthy subjects (age: 27.8$\pm$5.0, all males) participated in this study for two times (2 sessions) on different days. The subjects were asked to intentionally modulate the music feedback in the closed-loop application of the system according to specific tasks. The subjects were not given explicit information about how to achieve the modulations, but rather asked to develop individual mental strategies. The results showed that 3 out of of 5 subjects achieved statistically significant modulations of the music feedback. In order to intentionally modulate the feedback, all subjects stated to have retrieved emotional memories or imagined happenings they look forward to in order to self-induce emotions corresponding to the given modulation tasks.

IV. Discussion and Future Work

Closing the loop allows BCI users to monitor their own brain processes, which can trigger awareness, learning, recovery or even enhancement of brain functionality (neuroplasticity). Effective treatment protocols have been developed for different neurological disorders, among others for stroke [15], and depression [16]. The concept of systematically investigating the human brain while being embedded in a BCI-loop has been highlighted by Brunner *et al.* in 2015 as a promising key future field of BCI application [17] - utilizing BCI as a *research/experimentation tool*. Wander and Rao noted that the most promising entry point to this avenue is the study of sensorimotor processing loops in motor imagery-based BCIs [18]. A few studies have raised and discussed the question of how the concept of closing the loop via sound could be utilized for systematic investigation of the brain in the loop or potential directions towards innovative neurorehabilitation protocols [19]. To date, this approach is rather hypothetical and has not yet been systematically explored.

With the work presented in this paper we aim to set an entry point to this avenue. Musical stimuli permit the study of perception-action (sensorimotor) coupling as well as joint action and entrainment via reciprocal prediction and adaptation [20]. In future work, we are particularly interested in deepening the understanding of human sensorimotor integration in which musical sequences enable action upon the environment via entrainment. This could affect several populations who would benefit from the facilitation of sensorimotor integration (the closed loop): for example those affected by Parkinson's disease [21] or congenital music disorders [22].

V. Conclusion

We have presented the concept, technical realization and evaluation of a non-invasive BCI to establish affective closed-loop brain interaction by means of a music-based emotion display. The BCI is based on an algorithm (composing unit) to generate continuous patterns of synthesized affective music employable as a controllable emotion stimulus. We validated our BCI concept in two studies. In our first study we successfully evaluated the affective quality of synthesized musical patterns generated with the composing unit. In our second study we successfully evaluated the establishement of affective closed-loop interactions. The proposed BCI provides a platform to affectively stimulate the brain in a closed-loop fashion, offering novel approaches to study human sensorimotor integration and emotions.

Acknowledgment

The authors would like to thank the staff and students from the Brain Computer Interface Lab, Institute for Infocomm Research (I2R), Agency for Science, Technology and Research (A*STAR), Singapore. This research is supported by Deutsche Forschungsgemeinschaft (DFG) through the International Graduate School of Science and Engineering (IGSSE), Technische Universität München, in collaboration with Georgetown University, USA, and the University of Jyväskylä, Finland[3].

References

[1] A. Damasio, *Descartes' error: Emotion, reason and the human brain*. Vintage Digital, 2008.

[2] R. J. Davidson, "Affective style and affective disorders: Perspectives from affective neuroscience," *Cognition & Emotion*, vol. 12, no. 3, pp. 307–330, 1998.

[3] R. W. Picard, *Affective computing*. MIT press, 2000.

[4] J. Russell, "A circumplex model of affect." *Journal of personality and social psychology*, vol. 39, no. 6, p. 1161, 1980.

[5] S. M. Alarcao and M. J. Fonseca, "Emotions Recognition Using EEG Signals: A Survey," *IEEE Transactions on Affective Computing*, 2017.

[6] S. Ehrlich, A. Wykowska, K. Ramirez-Amaro, and G. Cheng, "When to engage in interactionand how? eeg-based enhancement of robot's ability to sense social signals in hri," in *Humanoid Robots (Humanoids), 2014 14th IEEE-RAS International Conference on*. IEEE, 2014, pp. 1104–1109.

[7] A. S. Widge, D. D. Dougherty, and C. T. Moritz, "Affective brain-computer interfaces as enabling technology for responsive psychiatric stimulation," *Brain-Computer Interfaces*, vol. 1, no. 2, pp. 126–136, 2014.

[8] A. Lucier, "Statement on: music for solo performer," *Biofeedback and the Arts, Results of Early Experiments. Vancouver: Aesthetic Research Center of Canada Publications*, pp. 60–61, 1976.

[3]"INTERACT: Brain-To-Sound Computer Interfaces: Neurofeedback of Music for Entrainment, Interaction and Neurorehabilitation" http://www.igsse.gs.tum.de/index.php?id=85

[9] S. Makeig, G. Leslie, T. Mullen, D. Sarma, N. Bigdely-Shamlo, and C. Kothe, "First demonstration of a musical emotion BCI," *Affective Computing and Intelligent Interaction*, pp. 487–496, 2011.

[10] T. De Smedt and L. Menschaert, "VALENCE: affective visualisation using EEG," *Digital Creativity*, vol. 23, no. 3-4, pp. 272–277, 2012.

[11] T. A. Deuel, J. Pampin, J. Sundstrom, and F. Darvas, "The Encephalophone: A novel musical biofeedback device using conscious control of electroencephalogram (EEG)," *Frontiers in human neuroscience*, vol. 11, 2017.

[12] I. Wallis, T. Ingalls, E. Campana, and J. Goodman, "A rule-based generative music system controlled by desired valence and arousal," in *Proceedings of 8th international sound and music computing conference (SMC)*, 2011.

[13] P. Gomez and B. Danuser, "Relationships between musical structure and psychophysiological measures of emotion." *Emotion*, vol. 7, no. 2, p. 377, 2007.

[14] G. J. Hagerer, M. Lux, S. Ehrlich, and G. Cheng, "Augmenting affect from speech with generative music," in *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems*. ACM, 2015, pp. 977–982.

[15] K. K. Ang, C. Guan, K. S. G. Chua, B. T. Ang, C. Kuah, C. Wang, K. S. Phua, Z. Y. Chin, and H. Zhang, "Clinical study of neurorehabilitation in stroke using EEG-based motor imagery brain-computer interface with robotic feedback," in *Engineering in Medicine and Biology Society (EMBC), 2010 Annual International Conference of the IEEE*. IEEE, 2010, pp. 5549–5552.

[16] R. Ramirez, M. Palencia-Lefler, S. Giraldo, and Z. Vamvakousis, "Musical neurofeedback for treating depression in elderly people," *Frontiers in neuroscience*, vol. 9, 2015.

[17] C. Brunner, N. Birbaumer, B. Blankertz, C. Guger, A. Kübler, D. Mattia, J. d. R. Millán, F. Miralles, A. Nijholt, E. Opisso *et al.*, "BNCI Horizon 2020: towards a roadmap for the BCI community," *Brain-computer interfaces*, vol. 2, no. 1, pp. 1–10, 2015.

[18] J. D. Wander and R. P. Rao, "Brain–computer interfaces: a powerful tool for scientific inquiry," *Current opinion in neurobiology*, vol. 25, pp. 70–75, 2014.

[19] A. Väljamäe, T. Steffert, S. Holland, X. Marimon, R. Benitez, S. Mealla, A. Oliveira, and S. Jordà, "A review of real-time EEG sonification research." Georgia Institute of Technology, 2013.

[20] R. J. Zatorre, J. L. Chen, and V. B. Penhune, "When the brain plays music: auditory-motor interactions in music perception and production," *Nature reviews. Neuroscience*, vol. 8, no. 7, p. 547, 2007.

[21] C. Nombela, L. E. Hughes, A. M. Owen, and J. A. Grahn, "Into the groove: can rhythm influence parkinson's disease?" *Neuroscience & Biobehavioral Reviews*, vol. 37, no. 10, pp. 2564–2570, 2013.

[22] J. Phillips-Silver, P. Toiviainen, N. Gosselin, and I. Peretz, "Amusic does not mean unmusical: Beat perception and synchronization ability despite pitch deafness," *Cognitive neuropsychology*, vol. 30, no. 5, pp. 311–331, 2013.