Brain-Computer Interfaces, 2015
Vol. 2, Nos. 2–3, 60–69, http://dx.doi.org/10.1080/2326263X.2015.1104613

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Artistic brain-computer interfaces: the expression and stimulation of the user's affective state

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(*Received 13 April 2015; accepted 4 October 2015*)

Science, technology, engineering, and mathematics (STEM) is rapidly transitioning to STEAM, which is the integration of the arts and design into the sciences. This transition is due to the need of adapting creativity in the sciences and engineering fields. This demonstrates the growing importance of the arts contribution towards the sciences in various ways. An area where art shows promise is in brain-computer interfaces. In this paper, we propose a definition for artistic brain-computer interfaces (artistic BCI) from a passive BCI perspective. We defined its composition in four fields: human-computer interaction, neurophysiology, art, and computing. This definition is based on the user's state stimulation and expression and how art could help us and the end user understand the user's affective state. We also discuss its applicability towards different areas and how these areas can benefit from artistic BCI.

Keywords: artistic brain-computer interfaces; artistic BCI; affective BCI; human-computer interaction; user experience

Introduction

A brain-computer interface (BCI) is a direct communication between the brain and a neurophysiological device. BCIs are adapted to manipulate machines' actions cognitively and to measure and identify the affective and cognitive state of the user. BCI was introduced for the first time by Jacques Vidal in 1973.[1] Since its introduction, it has been traditionally researched in the medical field with the focus on developing assistive technologies for people with disabilities. BCI is constructed of three main categorizations: passive BCI, active BCI, and reactive BCI.[2]

- Passive BCI: it uses the user's brain activity output to distinguish the user's affective/cognitive state for the purpose of enriching the human-machine interaction. It does not concentrate on voluntary control.
- Active BCI: it is the use of the user's brain activity output for controlling an application or various types of machines. This is independent from external events; therefore, it is not based on stimulations caused by external variables.
- Reactive BCI: it is similar to active. In this case, the user's brain activity output for controlling an application or machine is dependent on external events.

In recent years, the explosion of ubiquitous non-invasive BCI devices (Figure 1) has helped non-clinical researchers implement BCI methodologies in the field of human-computer interaction (HCI) with a focus on designing, developing, and evaluating human-centric applications for users without mental or physical disabilities. Furthermore, HCI researchers have become more interested in the use of BCIs due to their potential to help the researchers understand how the human brain behaves in various events. With help from non-medical researchers, designers, and developers, BCI applications have expanded from medical applications to applications for entertainment, non-neuroprosthesis and non-medical device control, and measurement/enhancement of hedonic experiences. BCI may consist of several activities:

- the measurement and processing of the user's brain activity with a neurophysiological device;
- the translation of brain activity to affective and cognitive states (user-state monitoring);
- the adaptation of a system based on a user's brain activity;
- changes to the physical or virtual environment based on a user's state;
- the translation of brain activity towards user's intention for device control;
- the evaluation of existing systems based on the user's behavior and brain activity.

Many of the major aforementioned activities are a reflection of the meaning and purpose of affective BCI. Affective BCI focuses on the understanding and manipulation of the user's affective state through a non-invasive wireless/non-wireless wearable neurophysiological device.

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Figure 1. Current wearable BCI devices (from left to right): OpenBCI 3D printed EEG headset, Emotiv EPOC, Emotiv Insight, Interaxon Muse, Neurosky Mindwave, Melon.

This includes the understanding of human nature, behavior, interaction with the physical and virtual worlds, decision-making, perception, memory, engagement, and others.[3] The human affective states are gathered from different brain areas: amygdala, insula, pre-frontal/frontal cortex, and the anterior cingulate gyrus. In the field of HCI, researchers can create (this involves the design and development process) applications that benefit from the ability to detect the user's affective state. The detection of the user's affective state could help researchers improve their systems to elicit a positive emotional state. For example, the measurement of the levels of engagement when the user is interacting with an application can aid towards the identification of the strengths and weaknesses of the application. Certain interactions may trigger a drop in engagement for the users; this may be implied as the weakness that needs to be redesigned.

In this paper we define artistic BCI from a passive BCI perspective, the elements it consists of, and how it could be applied across different areas such as gaming, wearables, user to user telecommunication, smart homes, the workforce, entertainment, human-robot interaction, and education. We describe how artistic BCI can be used as a stimulus and/or as an expression through these areas. This paper also presents general information about artistic BCI from both passive and active BCI perspectives, but will focus on passive BCI through the different applications and by providing unique examples different from [4].

Artistic brain-computer interfaces

Artistic BCI applications were introduced years before assistive BCIs. In 1965, the American composer Alain Lucier, of experimental music and sound installations, composed the 'Music for Solo Performer'. This composition was performed in real time using his electrical brainwaves through electroencephalographic (EEG) channels. His composition was based on amplified alpha rhythm. It was mentally controlled, which enabled the control of percussion instruments. As early as the 1970s, in artistic explorations of EEG brain activity measurements we often see artists exploring the brain activity patterns of two users or more to create a playful application or a piece of art using BCI input.[5] Figure 2 is a good example of an artistic representation of the brain. An example of utilizing artistic BCI with images similar to this is by correlating each color to a different affective meaning. The areas with an increased number of rays going outward in the image could map the intensity of the user's affective state.

Artistic BCI is a form of affective BCI that focuses on the understanding of the user's affective state through artistic forms. In 2013, Gürkök and Nijholt introduced and formalized the idea of artistic BCIs and its three categories: audification/visualization, musification/animation, and instrument control. They provided examples of previous work based on EEG devices that can relate to artistic BCI and their components. They also provided recommendations on how to develop artistic applications using affective BCIs.[4] We used this paper as motivation and gathered the presented knowledge of previous work in affective BCI and other areas to provide a formal definition for artistic BCI. Examples of how artistic BCI can be applied in different application areas are also presented.

Artistic BCI from a passive BCI perspective can be defined as a visual and audial representation of the user's affective state identification. It can take the form of a stimulus or a user's affective expression. The *stimulus* is used to elicit the user's affective state from negative to

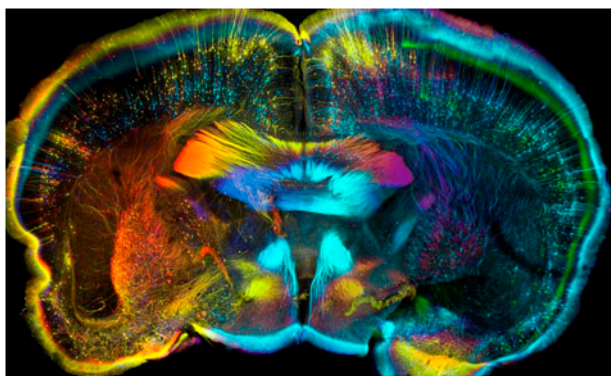

Figure 2. Visualization example of a brain. This image is taken from http://www.theverge.com/2015/3/11/8,190,681/wellcome-images-science-photography-2015.

positive and help them keep a positive emotional state. The stimulus can take the form of a sound, music, video, picture, or anything that affects the user's state. The *expression* is the representation of the user's state visually or through a type of audio where the corresponding user and others are able to see visually or hear how the user is feeling. It also serves as assistance that helps users see how others are feeling when interacting with them or other entities. These forms of artistic BCIs will be explained further in the areas as examples. It can be said that artistic BCI consists of three major components:

- a visual or audial representation of the user's affective and cognitive state;
- conversion of the brain signals to control commands for virtual and real artistic instruments; well adapted implementations of control are motor imagery, event-related potential (ERP) (i.e. P300), and steady-state visually evoked potential (SSVEP); These serve as different methods of control;
- the use of the brain rhythms to compose sound and draw visualizations; this does not serve as the representation, but as the control.

Artistic BCIs are also a way to create art for physical and virtual environments through cognitive control using a BCI. Artistic BCI may consist of four major fields (Figure 3): art, HCI, computing, and neurophysiology. These fields contain knowledge and tools, which can help the field of artistic BCI progress and become more established. Through art, design principles such as how people perceive various colors and shapes are studied. Neurophysiology helps us understand more about how the human brain functions through different events and

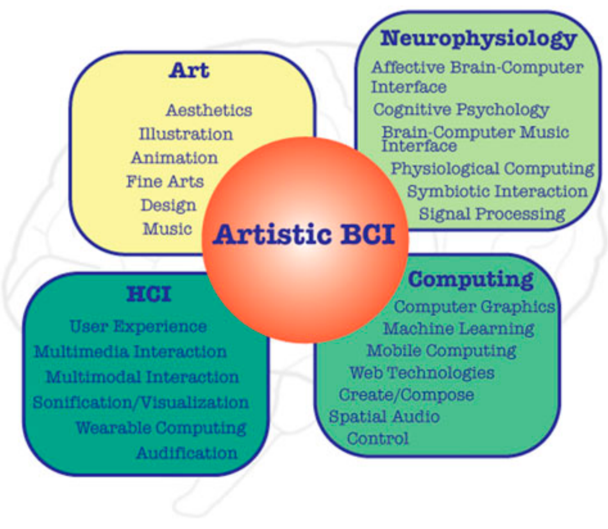

Figure 3. The four major fields that constitute artistic BCI.

conditions. HCI provides knowledge about how applications can be usable for humans to enrich the user experience and facilitate their lifestyle. Computing is the area used to apply the principles of the other three fields in order to build efficient applications.

Implementation of artistic BCI across different application areas

Artistic BCI can be implemented in the different aforementioned forms (expression and stimulus). The examples provided in this section were inspired by the statement presented by Gürkök and Nijholt:

> 'If art means to express emotion, then through art we might understand what emotion we are experiencing. If this is the purpose, then it might be desirable that the produced art piece is a simple one and interactive one so that the artists can understand the relation between their inner state and influence on the product.'[4]

Every provided example assumes a user is wearing a BCI, either EEG or a functional near-infrared spectroscopy (fNIRS) technology. Also, in some cases, we assumed the BCI devices are robust enough for both stationary or on-the-go tasks, although currently they need improvement. The examples provided below may also serve as start-up ideas of different artistic BCI applications that may be researched.

Gaming

There have been several debates as to whether video games are or are not considered art. Aaron Smuts, the author of 'Are Video Games Art?' supports the notion that they are. In his article, he offers many reasons to support his claim, including the fact that there are clear thematic continuities between video games and the history of Western literature as well as the fact that games share expressive goals with other recognized forms of art.[6] In [7] a theory is developed where video games are seen as aesthetic objects, which supports the claim that video games are a type of art.

Museums like the Museum of Modern Art (MOMA) in New York, USA, have started to incorporate video games such as Pacman (Figure 4) as a showcase. In 2013, at the Human Factors in Computing Systems Conference, also known as the Computer-Human Interaction (CHI) conference, Paola Antonelli, the Director of MOMA, explained that video games are a form of interaction design and therefore may be a form of art. She expressed the idea that design is a higher form of creative expression. Video games allow gamers to be creative when competing with other gamers or when solving puzzles to pass an obstacle. We should ask ourselves, if design is a form of art and video games are a

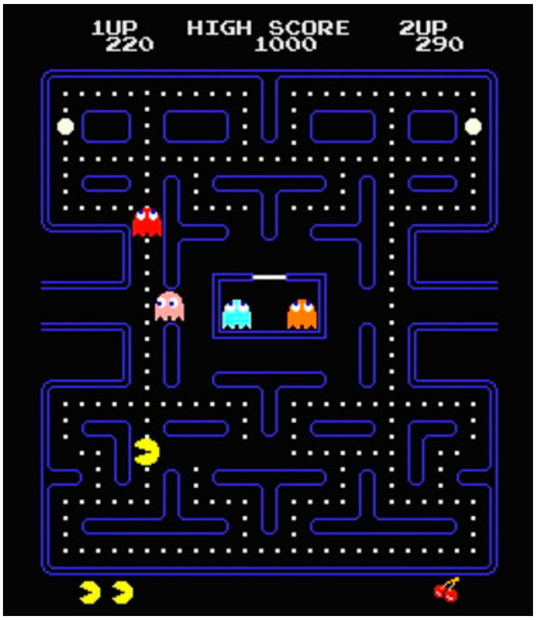

Figure 4. Pacman video game. This image is taken from http://www.fashionforwardtrends.com/man-of-the-moment-pac-man.

form of interaction design, are not video games a form of art by nature?

In video games, stimulus and expression are evident. The graphic's color of the game can serve as a stimulus to get the gamer's state to fit the theme of the mission. For example, Figure 5 shows the movie *Her*, in which the actor plays a video game where his living room is immersed in the video game. The lighting of the game at that current time is green, not for any particular purpose. From an artistic BCI view, the gamer wears a BCI device and transmits the affective state to the game; the graphic's colors can change to stimulate the affective state to fit the theme of the mission and have a more realistic gaming experience.

Figure 5. Gamer immersed in the video game. This image is taken from http://www.feelguide.com/2014/10/06/that-stunning-video-game-from-the-movie-her-will-soon-be-a-reality-thanks-to-microsoft/.

Researchers are looking at improving BCI as a method of interaction for gaming. Most of the current work is on using brainwaves to control the virtual characters in video games.[8,9] There has also been work on game-like applications that allow users to paint through active BCI.[10] In the future, affective data can be used to affect how the game is actually visually rendered. If gamers are wearing a BCI device while playing video games, the representation of the graphics (color intensity) could be determined by their affective state to either represent it or attempt to mediate their current state. If gamers are sad, the color selections for the environment represent the user's emotion. Additionally, the weather conditions in the game could reflect their affective state. For example, when the gamers are experiencing anger, thunderstorms may be a good representation of their emotion. This would be an interesting application in multi-player online games, where the gaming environment is based on the host's affective state. When gamers are playing games like *Grand Theft Auto*, during online multiplayer missions, the session host can set the weather conditions. In the game, the lighting of the game can be changed to a sunset, rain, snow, or really sunny. This is a similar idea, except the condition will be set based on affective data and not manual selection. In addition to the environmental changes, affective data could influence the appearance of a user's avatar. A good example of shape-shifting avatars based on the user's affective state is the Alpha *World of WarCraft* (WoW). WoW is a massive-multiplayer online roleplaying game designed and developed by Blizzard Entertainment. The affective edition of WoW allows the avatar to shape-shift based on the user's alpha activity. When the user is agitated, the avatar takes the form of a bear and shows its eagerness to fight, whereas when the user is relaxed, but alert, the avatar shape-shifts to a mentally adept night elf.[11]

Many games on the market now allow players to dictate the demeanor and attitude of their avatars. Instead of selecting an arbitrary demeanor once, using affective data could offer close to real-time representation of the players' true demeanor. Imagine two people are playing an intense online game; players may be interested to know when their opponent gets angry, flustered, or even confident. This type of feedback is currently given to users through the ability to verbally communicate, if they choose to enable their microphones and interact with each other.

Wearables

Electronic devices that are body-worn are known as wearables. They take various forms: wristband, headband, jacket, shirt, helmet, glasses, and more. Some researchers have even explored 'Beauty Technology', which hides electronic components in existing beauty products such as temporary tattoos, conductive makeup, and acrylic nails.[12] They are adapted for various types of events. Aside from the obvious fact that a BCI device could itself be considered a 'wearable', there is an opportunity for a deeper relationship where other wearables use the power of a BCI device. Visualization is an important component for many wearables and is a form of art. Projects like [13] are using affective data to create a 'mood-ring'-like bracelet. The bracelet's LEDs light up in different colors based on the user's current emotional state. The purpose of the bracelet is to help users regulate their emotional state. This idea could be expanded to other jewelry items as well as clothing. Wearables with emotional intelligence can be used to inform the wearers about themselves or to communicate their emotional state to others (Figure 6). In either case, the use of colored lighting is an artistic representation of affective data.

Wearables are a great way to explore interesting challenges in the data visualization space, particularly the challenges associated with visualizing emotion and affective data. One of the motivating factors for [13] was that 'Current neurofeedback interface devices are not designed to be used on a daily basis and are not considered user-friendly'. The authors in [13] also mention the media equation theory,[14] which states that the way people interact with media and with other people is based on the same principles. This was a justification for using media in the form of a light on the bracelet to encourage engagement and understanding of one's own emotion. Wearable technology integrated into clothing could also benefit from artistic BCI. Sharing affective data with these wearables could provide a stylish way for users to express their affective state. To achieve this, art could be displayed on screens attached to clothing. These screens could be used to reflect the user's state.

Figure 6. Clothes portraying lights from the movie *Tron*. This image is taken from http://collider.com/tron-3-tron-legacy-sequel-news-joseph-kosinski.

Images with colors and themes correlated with a user's emotion could be displayed dynamically. The current and future wearable BCIs can benefit from visualization integration. The BCIs can display different light patterns and colors (i.e. red can represent upset or disgust, or blue representing relaxation or peacefulness) to express the user's affective state.

The authors of 'Future Fashion' present two concepts they feel will be important to interpret the fashion of the future: fungility (exchangeability) and empathy. They make the argument that beyond aesthetic design, 'Fashion will engage with the flow of information and integrate seamlessly with the physical environment'. As a part of that seamless integration, the authors predict that in the future, fashion will create changes, movements, colors, and sounds to communicate brainwaves.[15]

User-to-user telecommunication

In this era, human-to-human conversation is performed in different ways. Each type of non-face-to-face communication has the limitation of one or both users not knowing how the other user feels when certain topics are being introduced. In the case when two users are texting each other, it is very difficult to understand what kind of emotion the other person is experiencing. Emoticons help the users to convey certain emotions, but their usage and meaning may vary by culture, gender, and generation. Also, certain words are capitalized to express yelling, but yelling can express both negative and positive emotions. If users are able to interpret how the other user is feeling when they are conversing, then the conversation may have a more positive impact. In this case, providing a visual feedback feature within the texting application that indicates the current user's affective state would be useful. Both users would wear a wearable BCI device that decodes their brainwaves to an affective state that is then displayed in the application. The visual feedback would represent the user's emotional status. This visual feedback could be represented through various colors, shapes, or symbols. A simple example could consist of red representing the user as angry and blue meaning s/he is peaceful. This can also be helpful when the user is about to call someone. Before calling that person, the application can show the affective state; this would allow the user to determine whether it is an appropriate time to have a particular conversation. This presents a good way to express emotions and assist users to have more successful and positive conversations. As artistic BCIs take the form of visualization composed of different colors and patterns, it could serve as a form of expression. The expression would be the visual feedback associated with the affective state of the user when conversing through text or phone call. Chanel and Mühl have started to discuss the use of physiological signals to improve social interactions. Based on their observations from previous studies for other HCI purposes, they concluded that physiological measures may have the potential to enhance social interactions and connect people.[16]

Smart homes

A smart home is an environment that provides ambient intelligence and automatic control to its residents.[17] This technology often facilitates common everyday tasks. Smart homes could also provide interactive art for users. Most of the previous work in the area of BCI and smart homes focuses on direct control via active BCI.[18] Previous work suggests that the use of physiological data with interactive art is promising.[19] Artistic BCI in smart homes could be represented in many forms. One of the implementations of art in smart homes is informative art.[20] Informative art is used to communicate useful information in an appealing manner to users. Pairing interactive informative art with artistic BCI could provide new ways for users to apply designs to their home. These dynamic designs could also be used to stimulate the user state. For example, if a user gets frustrated, the smart home system could alter art in the home to assist users with calming down. This same concept could also be applied to physical visualizations like fireplaces or indoor artificial water falls. Mapping artistic BCIs to settings such as light intensity and color in ambient environments could present novel ways to communicate or stimulate emotions. Ambient lights in the home can also be used to produce art using affective data. Art in homes is commonly used to express things such as personality, themes, and emotions. Artistic BCI could provide a way for users to passively influence design while expressing various emotions. Art in some cases is used to decorate the exterior section of homes. Exterior home decorations range from water fountains to outdoor light fixtures. As more advances are made in Internet of things (IoT) research, smart home functionality will spread beyond devices located inside homes. This could present an opportunity to use artistic BCI with exterior home decorations based on affective data. One example of this is modifying lights by a pool or patio based on the user's state. Artistic BCI could also be used to modify exterior art to stimulate a user state while the user is outside. The way that homes are decorated is how users are expressed. The use of artistic BCI can strengthen that connection between the home and the emotional characteristics of users.

Workforce

As the market for BCI applications for healthy users becomes more promising, interest from industry may also increase. A preliminary study investigating marketability suggests that BCI researchers are optimistic about the amount of time it will take BCI devices for healthy users to reach the market.[21] This work also suggests increased marketability could result in industry adoption. Many tools such as word processing and spreadsheet applications have become very common in the workplace. This was not always the case prior to the software applications becoming established and efficient. Similar to how these applications increased productivity for businesses, BCI could also optimize working conditions. Previous work suggests that online BCI systems could assist with avoiding hazardous scenarios by detecting certain cognitive states.[22] Artistic BCI could be used to communicate the state of employees in these scenarios. Employee morale is also an important factor for many businesses. Currently, this is commonly measured through employee satisfaction surveys. Although surveys are currently one of the most efficient ways to analyze satisfaction, they could present issues when anonymity and data accuracy are questioned. BCI presents a way to capture affective data that could provide results that are more reliable than standard surveys. In order to avoid anonymity issues, employee affective data should not be uniquely linked to individuals. Furthermore, the data should mainly be used to observe the average emotional states among units or the entire company. Artistic BCI comes into play during the analysis phase. Visualizations based on the collected affective data could be used to communicate the employee population morale and/or motivation. This visualization could also be presented as on-screen art and placed in certain areas in businesses. This approach could assist management understand thoroughly their employee emotional state.

Another great example of BCI visualization in the workplace is the [23] project that emerged from the MIT Media Lab. With the growing popularity of open floor plans for modern work environments, they developed a system that would help combat some of the negative trade-offs of the growing trend. For example, although the open floor plans can help boost creativity and encourage social interactions, they can reduce privacy along with workers' focus and productivity. The transparent system uses the NeuroSky device to capture EEG signals and measure a user's focus. The user's level of focus and availability is visually communicated to other workers by changing the opacity of a glass wall. When the level of focus and need for privacy is high, the wall's opacity increases. Once the focus level decreases, the wall becomes more transparent. Similarly, work has been done to investigate the use of neurophysiological signals to support social interaction, which is being called social signal processing (SSP).[16] They are investigating the affective exchange between members of a group to determine 'group mood', similar to the group-think phenomenon. This work stretches beyond the traditional affective evaluation for only emotional states; it evaluates disagreement, ambivalence, and attention. The notion of a group mood could have interesting implications not only in a workplace setting, but also in a more social setting as well. Although artistic BCI is not quite ready for major use in the workplace, it has great potential to serve as both a utility and a tool to create art. Measuring morale and presenting it via artistic BCI also could apply to other more social settings such as the entertainment domain.

Entertainment

Using BCI for entertainment purposes has recently gained popularity.[11] Most of the work on entertainment BCI is focused on the gaming domain as discussed in the gaming section. In this section, we discuss nightlife entertainment that could benefit from artistic BCI. Previous research suggests that artistic BCI can assist with driving novel context-aware applications.[24] Artistic BCI could be integrated into these applications. One example of how artistic BCI could be applied is through interactive dance performances. There has been work that looks into how physiological data can be used to influence sound and light during dance performances.[25] There has also been work investigating the possibilities of crowd interaction with art in social environments.[26] Research similar to these works suggests that physiological data could be used to express art in nightclub environments. One potential use is reflecting the user's affective state through nightclub lights (Figure 7) on a big artistic visualization screen. These lights can display a large array of different colors at various levels of intensity. They are often mounted to ceilings and project colorful light displays on a nightclub's floor. The lights are sometimes equipped with motors that

Figure 7. Illustration of colorful lights in an entertainment place. This image is taken from http://imgkid.com/clubbing-lights.shtml.

enable movement. This presents the possibility of mapping affective data not only to light intensity and color, but also to motion. Suppose the mood of the club attenders suddenly spiked. Using artistic BCI, this could be expressed through the lights in the club to provide a more personal and natural experience. Artistic BCI could also be used in this setting to represent or stimulate the users' state through audio. An example of this is playing certain sound effects to engage dancers when their attention levels drop; a good example of sound/music is electronic dance music (EDM). Although there must be much work on filtering noise caused by users' movement and sweat before this concept can become a reality it presents a novel approach to the use of artistic BCI in a social context.

Human-robot interaction

Recently, there has been an emergence in robotics oriented towards artworks. This artistic research has resulted in researchers working on projects that are less restricted to traditional robotic research. The artwork featured in the robotic domain ranges from dancing robots.[27] to quadrotor robots that give musical performances.[28] There has also been work on robotic systems that can produce virtual and physical art.[29,30] In recent years, scientists and artists with a common interest in robotics and the arts began creating communities. According to one previous work that investigates the Artbots community, robot art could be useful for creating interactive experiences.[31] Most of the existing work that integrates robotics and BCI focuses on communication and control. As a result, there is little to no work done on using artistic BCI with robots to create art. The integration of artistic BCI and robotics could result in many types of art forms. One way is to provide art-generating robots with the user's affective data. Based on the data received, these robots could create visualizations that represent or stimulate the user's state. This sharing of emotion could be done with a virtual or physical robot. Another form of BCI robot art could consist of driving the dance/movement behavior of a robot through a user's emotional state. This presents a way to represent the user's state through kinematic motion. This approach allows users to play a role similar to a ventriloquist. In this example, instead of using strings to control motion, the user's state is used. Similar to the previous work mentioned above, artistic BCI could also be used to create robot-generated music based on the user's state, which expresses the user's state through audio.

Education

The use of BCIs in the educational domain has been shown to be promising to assist learners. Researchers have mainly measured levels of engagement while users are learning and have adapted a custom-built tool to enhance the learning experience.[32,33] Other studies have focused on the comparison of learning techniques while wearing a BCI (Figure 8).[34] The adaptation of artistic BCI in education can be useful from an expression and stimulus perspective to assist teachers to identify in real time, or after the given task, the student's learning experience: for instance, a scenario where learners in a classroom are wearing a BCI and the teacher is able to monitor on his or her computer or mobile device when the students are engaged. The visualization type and the use of colors are the key to the data comprehension for both the teacher and students. The teacher should be able to understand the data fast and modify their teaching style to fit the majority of the student's learning styles. From the student's perspective, the ability to track his or her cognitive workload and engagement while doing certain homework can be a good metric to facilitate his or her study habit improvements.

Virtual and physical visualizations (projections)

The audial representation of the user's affective state has been well documented through the field of brain-computer music interfaces (BCMIs). The visual representation of the brain activity is an important aspect to understand the user's affective state, but it has not been studied formally as the audial representation. Visualizations can be presented in many forms. These forms range from simple visualizations on computer screens or complex holograms. Each of these visual media types presents different ways to visualize and communicate data. Visualizations are currently commonly found on screens such as TVs, computer monitors, tablets, projectors, and computers. There has been previous work that utilizes on-screen visualizations for artistic BCI.[10,35] Another example of this is representing affective brain signals via a particle system.[36] An additional positive feature of on-screen visualization is its ability to change dynamically based on a user's state. Unlike some forms of physical visualizations, these visualizations need to be changed in real time. To take advantage of this feature a user's state can be recorded over time and used to render art that corresponds to the user's changing state. An additional bonus for on-screen visualizations is the limited amount of resources that it needs. Many of the examples mentioned in the aforementioned sections only require a computer screen and a BCI device.

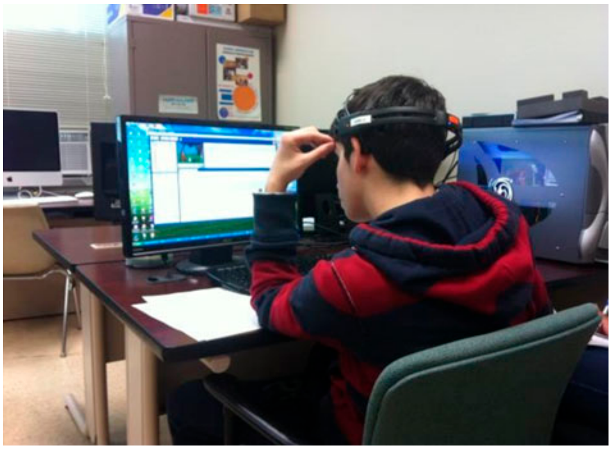

Figure 8. Student completing a class assignment while wearing a BCI.

Although much of the focus of visualization lies in the virtual space, physical visualizations could also be useful for artistic BCI. Humans have interacted with physical visualizations since 5500 BC.[37] As a result, humans are naturally proficient at understanding physical affordances and structures that appear in the real world. In the physical domain, visualizations are not constrained to pixels. Instead of pixels, elements such as physical matter, liquids, and gasses can be used to display visualizations.[38] Physical matter-based visualization produces objects that can be touched and observed in the real world. This enables users to utilize multiple senses (visual and touch) when interacting with a physical visualization. Mapping information collected from a BCI to different types of textures and structures could provide interesting pieces of art. One way to generate physical structures from affective data is by utilizing 3D printing technology with BCI. These physical pieces of art could be used to symbolize memories or experiences. They could also serve as souvenirs, jewelry, and other items used to physically capture and share emotions. Along with physical matter, light also influences human visual senses. Researchers have recently investigated using lights to reflect a user's emotional states.[39] Water is also a physical element that can be used to display art. Previous work investigated ways to use water to generate various forms of visualizations.[40,41] These examples show that ambient displays featuring water could serve as a way to visualize data from a BCI.[42] Along with physical matter and liquids, fire can also be used as a physical visualization. Previous work suggests that fire can work as a visualization.[43] Fire can be used to engage users' visual and somatic senses dynamically. Being able to see and feel BCI-generated art change dynamically could provide a unique experience for users. The examples listed above represent only a few ways physical visualization can be used to express art. Although they may require more resources, physical visualization provides opportunities for art to engage more senses than virtual visualizations.

Current wearable BCI challenges

Current wearable BCI devices offer low cost expenditure, flexibility, and a wider variety of applications for different purposes. However, the channel quality of the wearable BCIs is not as robust as the traditional BCIs yet, which restricts the adaptability of artistic BCI applications. It requires the user to stand still, restrict muscle movement as much as they can, have a certain type and length of hair, and be in a room that is at a decent, cold temperature to avoid sweat. These requirements do not allow the user to perform a real-world task in a natural manner and may negatively affect how they feel about BCIs. An ergonomic issue is that these BCIs are not adjustable for all the different types of head shapes and sizes. Each device has its own limitation on how they can be worn and who can wear them.

The current states do not allow researchers to identify the user's affective state for all the different possible scenarios. At this instance, these devices are more functional in a stationary position, while real-world tasks are not always stationary. Through different research studies, recommendations on how to advance this technology for universal adaptation of users performing real-world tasks or laboratory experiments may be beneficial. Artistic BCIs are still able to use these devices for the identification of the user's affective state and express it visually, through audio, or a combination of both.

Conclusion

We discussed the integration of BCI and the arts and how it was introduced many years ago. We provided a definition of artistic BCI and how it can be applied in different application areas: gaming, wearables, user-to-user telecommunication, smart homes, workforce, entertainment, human-robot interaction, and education. In each area, artistic BCI was explained in the form of expression or stimulus. Artistic BCI from a passive BCI view is composed of the visual and audio representation of the user's affective state. In this paper, we categorized artistic BCI into four major fields: HCI, computing, arts, and neurophysiology. The four fields serve as a minimum requirement towards the implementation of artistic BCI methodologies. Artistic BCI will assist users when detecting their users' affective state while they are performing real-world tasks.

Acknowledgements

This material is based in part upon work supported by the National Science Foundation under Grant Number DGE-1315138 & DUE-1060545. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

Disclosure statement

No potential conflict of interest was reported by the authors.

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References

[1] Vidal J. Toward direct brain-computer communication. In: Mullins LJ, editor. Annual review of Biophysics and Bioengineering. Vol. 2. Palo Alto: Annual Reviews Inc.; 1973. p. 157–180.
[2] Zander TO, Kothe C. Towards passive brain–computer interfaces: applying brain–computer interface technology to human–machine systems in general. J Neural Eng. 2011;8:025005.
[3] Mühl C, Allison B, Nijholt A, et al. A survey of affective brain computer interfaces: principles, state-of-the-art, and challenges. Brain-Comput Interfaces. 2014;1:66–84.
[4] Gürkök H, Nijholt, A. Affective brain-computer interfaces for arts. 2013 Humaine Association Conference on Affective Computing and Intelligence Interaction. IEEE; 2013. p. 827–831.
[5] Rosenboom D, editor. Biofeedback and the arts: results of early experiments. Vancouver: A.R.C. Publications; 1976.
[6] Smuts, A. Are video games art? In: Contemporary aesthetics p.3. 2005.
[7] Kirkpatrick C. Aesthetic theory and the video game. Manchester: Manchester University Press; 2013.
[8] van de Laar B, Gürkök H, Plass-Oude Bos D, et al. Experiencing BCI control in a popular computer game. IEEE Trans Comput Intell AI Games. 2013;5:176–184.
[9] Pires G, Torres M, Casaleiro N, et al. Playing Tetris with non-invasive BCI. In Serious Games and Applications for Health (SeGAH), 2011 IEEE 1st International Conference on. IEEE; 2011, November. p. 1–6.
[10] Münßinger JI, Halder S, Kleih SC, et al. Brain painting: first evaluation of a new brain–computer interface application with ALS-patients and healthy volunteers. Front Neurosci. 2010; 4:1–11.
[11] Plass-Oude Bos D, Reuderink B, Van de Laar BLA, et al. Brain-computer interfacing and games. In: Brain-computer interfaces. Applying our minds to human-computer interaction. Human-computer interaction series. London: Springer Verlag; 2010. p. 149–178.
[12] Vega KFC, Fuks H. Empowering electronic divas through beauty technology. In: Design, user experience, and usability. User experience in novel technological environments. Springer Berlin Heidelberg; 2013, p. 237–245.
[13] Hao Y, Budd J, Jackson MM, et al. A visual feedback design based on a brain-computer interface to assist users regulate their emotional state. In: Proceedings of the extended abstracts of the 32nd annual ACM conference on Human factors in computing systems – CHI EA '14 2014, 2491–2496.
[14] Reeves B, Nass C. How people treat computers, television, and new media like real people and places. Cambridge: CSLI Publications and Cambridge University Press; 1996.
[15] Flanagan PJ, Vega KFC. Future fashion–at the interface. In: Lecture Notes in Computer Science. Springer Berlin Heidelberg; 2013. p. 48–57.

[16] Chanel G, Mühl C. Connecting brains and bodies: applying physiological computing to support social interaction. Interact Comput. 2015;27:534–550.
[17] De Silva LC, Morikawa C, Petra IM. State of the art of smart homes. Eng Appl Artif Intell. 2012;25:1313–1321.
[18] Carabalona R, Grossi F, Tessadri A, et al. Home smart home: brain-computer interface control for real smart home environments. In Proceedings of the 4th international convention on rehabilitation engineering & assistive technology. Singapore Therapeutic, Assistive & Rehabilitative Technologies (START) Centre; 2010. p. 51.
[19] Edmonds E, Everitt D, Macaulay M, et al. On physiological computing with an application in interactive art. Interact Comput. 2004;16:897–915.
[20] Holmquist LE, Skog T. Informative art: information visualization in everyday environments. In Proceedings of the 1st international conference on Computer graphics and interactive techniques in Australasia and South East Asia. ACM; 2003. p. 229–235.
[21] Nijboer F, Allison BZ, Dunne, S, et al. A preliminary survey on the perception of marketability of brain-computer interfaces and initial development of a repository of BCI companies. In: 5th International Brain-Computer Interface Conference, BCI 2011, 22-24 September 11th, Graz, Austria. 2011. p. 344–347.
[22] Venthur B, Blankertz B, Gugler MF, et al. Novel applications of BCI technology: psychophysiological optimization of working conditions in industry. In Systems Man and Cybernetics (SMC), 2010 IEEE International Conference on. IEEE; 2010. p. 417–421.
[23] Ducao A, Tseng T, von Kapri A. Transparent: brain computer interface and social architecture. In ACM SIGGRAPH 2012 posters. ACM; 2012, August. p. 26.
[24] Gluhak A, Bandara U, Presser M, et al. UbiClub – A context-aware environment for nightclub entertainment and management, capturing context and context aware systems and platforms – Joint e-SENSE, MAGNET beyond, DAIDALOS, and CRUISE workshop. Island, Greece: Mykonos; 2006.
[25] Wechsler R. Computers and art: a dancer's perspective. IEEE Technol Soc Mag. 1997;16:7–14.
[26] Sheridan J, Bryan-Kinns N, Reeves S, et al. Graffito: crowd-based performative interaction at festivals. In CHI'11 extended abstracts on human factors in computing systems. ACM; 2011. p. 1129–1134.
[27] Michalowski MP, Sabanovic S, Kozima H. A dancing robot for rhythmic social interaction. In Human-Robot Interaction (HRI), 2007 2nd ACM/IEEE International Conference on. IEEE; 2007. p. 89–96.
[28] Bond J. Robot Quadrotors perform James Bond theme [Internet]. [cited 2015 Mar 14]. Available from: https://www.youtube.com/watch?v=_sUeGC-8dyk
[29] Greenfield G. Robot paintings evolved using simulated robots. In Applications of evolutionary computing. Springer Berlin Heidelberg; 2006. p. 611–621.
[30] Kudoh S, Ogawara K, Ruchanurucks M, et al. Painting robot with multi-fingered hands and stereo vision. Rob Auton Syst. 2009;57:279–288.
[31] Jacobsson M, Fernaeus Y, Cramer H, et al. Crafting against robotic fakelore: on the critical practice of Artbot artists. In CHI'13 extended abstracts on human factors in computing systems. ACM; 2013. p. 2019–2028.
[32] Huang J, Yu C, Wang Y, et al. FOCUS: enhancing children's engagement in reading by using contextual BCI training sessions. In Proceedings of the 32nd annual ACM conference on Human factors in computing systems. ACM; 2014. p. 1905–1908.
[33] Andujar M, Gilbert JE. Let's learn!: enhancing user's engagement levels through passive brain-computer interfaces. In CHI'13 extended abstracts on human factors in computing systems. ACM; 2013. p. 703–708.
[34] Andujar M, Ekandem JI, Gilbert JE, et al. Evaluating engagement physiologically and knowledge retention subjectively through two different learning techniques. In Human-computer interaction. Applications and services. Springer Berlin Heidelberg; 2013. p. 335–342.
[35] Sobell N. Streaming the brain. MultiMedia. 2002;9: 4–8. IEEE.
[36] De Smedt T, Menschaert L. VALENCE: affective visualisation using EEG. Digital Creativity. 2012;23: 272–277.
[37] Schmandt-Besserat D. Tokens: the cognitive significance. Documenta Praehistorica. 1999;21–27.
[38] Vande Moere, A. Beyond the tyranny of the pixel: exploring the physicality of information visualization. In Information Visualisation, 2008. IV'08. 12th International Conference. IEEE; 2008. p. 469–474.
[39] Hao Y, Budd J, Jackson MM, et al. A visual feedback design based on a brain-computer interface to assist users regulate their emotional state. In CHI'14 extended abstracts on human factors in computing systems. ACM; 2014. p. 2491–2496.
[40] Heiner JM, Hudson SE Tanaka K. The information percolator: ambient information display in a decorative object. In Proceedings of the 12th annual ACM symposium on User interface software and technology. ACM; 1999. p. 141–148.
[41] Dahley A, Wisneski C, Ishii H. Water lamp and pinwheels: ambient projection of digital information into architectural space. In CHI 98 Conference Summary on Human Factors in Computing Systems. ACM; 1998. p. 269–270.
[42] Artists Uses Brainwaves to Manipulate the Motions of Water. 2013, December 4. Available from: http://neurogadget.com/2013/12/04/artist-uses-brainwaves-to-manipulate-the-motions-of-water/9104
[43] NAODesign. 2006. infornoptix - digital pyrotechnic matrix, URL. Available from: http://www.infernoptix.com/