Chapter 12
Competing and Collaborating Brains: Multi-brain Computer Interfacing

Anton Nijholt

Abstract In this chapter we survey the possibilities of brain-computer interface applications that assume two or more users, where at least one of the users' brain activity is used as input to the application. Such 'applications' were already explored by artists who introduced artistic EEG applications in the early 'seventies' of the previous century. These early explorations were not yet supported by advanced signal process methods, simply because there was no computing support possible, and interest in artistic applications faded until it reappeared in more recent years. Research in neuroscience, signal processing, machine learning and applications in medical, assistive BCIs prevailed. It was supported by computer science that provided real-time and off-line processing to analyze and store large amounts of streaming or collected data. With the possibility to access cheap shared and distributed storage and processing power, as it became available in the last decade of the previous century and the first decade of this century, different kinds of BCI applications, following a general interest in digital games, interactive entertainment and social media, became visible. These are domains where experience, fun and emotions are more important than efficiency, robustness and control. BCI provides user and application with a new modality that can be manipulated and interpreted, in addition to other input modalities. This has been explored, but mostly from the point of view of a single user interacting with an application. In this chapter we look at BCI applications where more than one user is involved. Games are among the possible applications and there are already simple games where gamers compete or collaborate using brain signal information from one or more players. We consider extensions of current applications by looking at different types of multi-user games, including massively multi-player online role-playing games. We mention research —distinguishing between active and passive BCI—on multi-participant BCI in non-game contexts that provides us with information about the possibilities of collaborative and competitive multi-brain games and that allows us to develop a vision on such games. The results of the literature study are collected in a table

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where we distinguish between the various forms of interaction between players (participants) in collaborative and competitive games and team activities.

Keywords Brain-computer interfaces · EEG · Multi-brain games · Multi-player games · Social games · Collaborative decision making · Videogames

12.1 Introduction

Pervasive and ubiquitous computing requires multi-user interfaces for environments and devices that offer professional, recreational and social applications. These interfaces are also multimodal, and mouse, keyboard or joystick are joined by more natural input modalities including touch and gestures. Moreover, rather than providing these environments and devices with explicit input, their sensors also know how to monitor us and support us in our activities in pro-active ways. Multi-user applications, where sensor-equipped environments monitor users in order to support them in their activities or to provide useful information for the owners of the environments are being introduced. Obvious examples are home environments, office and meeting environments, but also multitouch tables and distributed game and entertainment environments that have multiple users. We may think of children using tangibles playing together in a sensor-equipped room or public space, but also of physically co-located players competing or collaborating in a videogame, or multi-user online games with physically distributed players. Apart from traditional input devices, there can be simultaneous input from multiple users using gestures, facial expressions, bodily movements and various kinds of natural or user-manipulated physiological input, including input provided by brain signals.

In previous years we have seen a growing interest in brain-computer interfacing (BCI) in the human-computer interaction (HCI) community. Before that, BCI was researched with the aim to help disabled persons and provide them, among other things, with a hands-free ‘communication channel’ to type messages, to control prostheses, or to navigate a wheelchair [2]. Our research, instead, has focused on BCI for ‘healthy’ users, in particular on its use for games [26, 30]. There are good reasons to do so. In games and entertainment applications we are not limited by thoughts and concerns that relate to patients and disabled persons. We can use our fantasy and can allow situations and events in non-real-life situations, happening in virtual worlds and videogames. We can allow cooperation and competition with multiple and distributed users and we can allow interaction modalities and effects that are unusual but nevertheless can be believable, given the context of the game. Gamers don’t behave as disabled people in need of support. They have different motivations and expectations. That introduces problems and new challenges. Game designers have to design for challenges or otherwise to make use of the existing challenges in a meaningful manner, rather than to avoid them.

In 2012 a roadmap for BCI research was published (eds Allison et al. [1]. The roadmap was initiated by the FP7 research program of the European Union. The roadmap stayed close to traditional BCI research. It hardly took into account new research opportunities coming from embedding BCI research in HCI research, in particular multimodal interaction [10, 27] and artificial intelligence research. The problems (or challenges) that were identified in the roadmap (reliability, proficiency, bandwidth, convenience, support, training, utility, image, standards and infrastructure) do also rise when we look at BCI for games, entertainment and artistic applications. However, they can be dealt with in a different way. A game is about challenges and an interactive art installation may be provocative and surprising rather than that it acts according to our expectations; it may allow teasing, frustrating [34] and deceiving. Hence, rather than being effective in a traditional sense, such applications are about manipulating experiences (van de Laar [17], and satisfying psychological needs (for example, showing competence in dealing with challenges and socializing) [11], and not necessarily about efficiency and convenience. Hence, such applications require knowledge about the affective state of the user [24]. Efforts to develop a new, more long-term, roadmap for BCI research are reported in [4].

A bottleneck that prevents wide-spread use of BCI is the set-up encumbrance. A standard configuration requires an EEG cap with several electrodes, it has to be positioned on the head of the user, gel is required between scalp and electrodes to get good signals, and only after ten or more minutes of preparation time the user is physically connected to the BCI device. Presently so-called 'dry' electrodes that don't require conductive gel and wireless connections have been introduced, reducing set-up time. Attractive headsets are now becoming available from BCI game companies. A second bottleneck is reliability. People can be trained to use a BCI, but not everybody can perform in a satisfactory way. BCI signals are subject-dependent and even for one subject there is variability depending on mood, emotions and fatigue. For certain applications repeated trials are needed in order to be able to make a decision about a mental state or to be able to map detected brain activity to appropriate control or communication commands. However, also for this bottleneck there are positive research developments such as progress in signal analysis, artifact removal methods, and machine learning. Moreover, for some applications, as we will discuss in this chapter, rather than recognizing brain activity of one user and deciding how to use it, we can have recognition of brain activity of many collaborating users involved in the same task. Maybe this multi-brain computer interfacing can lead to more reliable decisions and certainly it can lead to new and interesting applications of BCI.

Both for traditional BCI and multi-brain BCI it is useful to distinguish between active and passive BCI. Active BCI requires real-time or near real-time BCI. There is voluntary control of brain activity, meant to control an application. In a passive BCI situation the brain activity of a user is monitored. The user is not necessarily aware of this monitoring and does not attempt to steer it. This information can be used to adapt the environment, but not necessarily in real-time.

12.1.1 Organization of this Chapter

Taking into account these observations, in this chapter we discuss and survey current applications and ideas on multi-brain-computer interfaces, with the aim of using these ideas in future multi-brain BCI games and other future applications. We start in Sect. 12.2 by looking at early multi-brain applications, in particular 'applications' and ideas pursued by artists. They were among the first designers of BCI real-time interaction technology and their applications required the measurement of brain activity of interacting participants or the collecting of brain activity of audience members in order to have the (multimedia) environment and audience members react and interact. Other non-artistic applications involving EEG recordings of several users at the same time followed for example to measure audience appreciation of events or products or to or measure and analyze involvement and performance in collective tasks, either for real-time or off-line purposes. Section 12.3 is about two important characteristics of games: competition and collaboration. We look at existing multi-brain BCI applications with these two characteristics in mind. Section 12.4 provides an inventory of multi-brain BCI games from the point of view of numbers of participating collaborating and competing (teams) of gamers. In Sect. 12.5 we present a table in which we summarize characteristics of existing multi-brain applications with the observations of Sect. 12.4 (competition and collaboration) and 12.5 (users and teams) in mind. Finally, in Sects. 12.6 and 12.7, we have a discussion, have some observations on future applications and present some conclusions.

12.2 Brain Activity Measurements from Multiple Brains

Clearly, gamers use their brains to compete and to collaborate, hence, whenever more than one player is involved in a game we can talk about multi-brain games. But, of course, without explicit measuring of their brain activity it is better to speak of multi-user or multi-party games. Before looking more closely to what we call multi-brain games it is useful to have some remarks about multi-brain BCI applications in general. That is, applications where BCI is used in the context of information extracted from multiple brains. In Sect. 12.2.1 we review early artistic multi-brain BCI applications. Section 12.2.2 has some observations on useful, useful rather than playful, multi-brain BCI applications. Both sections introduce ideas and developments that help to introduce multi-brain BCI games in forthcoming sections of this chapter.

12.2.1 Early Multi-brain BCI Applications

Interestingly, artistic BCI applications date older than assistive BCIs. Consciously producing alpha states and monitoring them by EEGs was first described in

Kamiya's influential paper in *Psychology Today* [15]. Five years later Jacques Vidal, in another seminal paper, introducing the concept of 'brain-computer interfacing', asked how to put brain signals to work *"… in man-computer communication or for the purpose of controlling such external apparatus as prosthetic devices or spaceships …"* [41]. Kamiya's references to Zen and LSD may have sparked interest, but even before these publications we saw composers and musicians such as Alvin Lucier, Pierre Henry, Richard Teitelbaum, John Cage, and David Rosenboom show interest, experiment, compose and perform using brain signals. In the early seventies of the previous century Nina Sobell designed a brainwave drawing game where participants had to synchronize their alpha activity in a Lissajous visualization of their joint brain activity [36].

Many of these early artistic experiments are described in "Biofeedback and the Arts" (ed Rosenboom [35]. In a 1972 TV show David Rosenboom performed with John Lennon and Yoko Ono in a brainwave controlled interactive music performance. Sonification, visualization and modifying otherwise produced multimedia received attention. But there were other applications. One of them, 'Alpha Garden', designed by Jacqueline Humbert in 1973, had two persons control the flow of water through a garden hose and sprinkler system by synchronizing their alpha activity. Another one, also designed by Humbert in 1974, was 'Brainwave Etch-a-Sketch'. Here, two participants had to control their alpha waves, where one participant could move a dot on an oscilloscope along the x-axis, and the other participant could move the dot along the y-axis. In this way they could cooperate to produce a drawing on the screen. In another performance experiment ('Music from Brains in Fours') Rosenboom had brain activity of four musicians integrated with information about body temperature and galvanic skin response in order to provide input to a performance.

In these applications we see audio or visual representation of brain activity and the control of these representations. But also the voluntary or involuntary control or modification by brain activity of multimedia not directly produced from brain activity. And we see applications where synchrony between the brain activities of users guides such applications. It should be noted that in these early applications of multi-brain activity the possibility to analyze brain signals or to (machine) learn from previous interactions was extremely poor. That changed in later years.

Employing computers for artistic BCI applications required cooperation between artists and researchers in computer science, human-computer interaction, neuroscience and brain-computer interfacing. In the period 1975–2000 there are few interesting artistic applications of BCI, let alone multi-brain applications. In this period each of these areas had its own problems and challenges and they mainly focused on more efficient problem solving, rather than on providing users with artistic, emotional or entertaining experiences. This has changed considerably in our 21st Century. Interest in efficient problem solving, efficient searching, efficient access to information and access to (mediated) communication is of course still there. But now we can conclude that this technology is already available, not only to support our home and professional activities, but also our activities related to sports, learning, entertainment, and arts. That is, applications that become possible through advanced and efficient computer processing, but where this efficiency is used to offer the user the possibility to have fun, become entertained or relaxed, rehabilitate, or learn.

12.2.2 Current Multi-brain BCI Research and Applications

There are various kinds of applications where it is useful to know how people experience a certain event or product. We can have questionnaires, we can look at facial expressions and we can measure (neuro-) physiological characteristics of the potential users. The latter may yield information that is more reliable than that can be obtained by asking or observing participants in an experiment. For example, brain activity from multiple persons can be measured and analyzed for neuromarketing purposes. This can be done on an individual basis and there is no need to use the results of the analysis in real-time, that is, no feedback to the user is necessary in real-time. In neurocinematics [13] similarities in spatiotemporal responses across movie viewers are studied. Here, future applications may require real-time processing of such brain activity in order to have collective or individual decisions about the continuation of a movie while watching.

But, if we remain more closely to current BCI research activity, there is certainly more research in which multi-brain activity is investigated and where the immediate goal is not yet real-time applications, but where real-time applications, also in the context of games, can be foreseen or appear already in prototype applications. However, mostly, at this moment in this research no active BCI control by users is present. There is, for example, measuring and analyzing of brain activity of persons engaged in the same task. It is investigated how this engagement shows in their brain activity. But there can be an added aim to learn from this in order to support and improve this joint activity. This can then be done off-line, taking care of better conditions for future joint activity. And one step further, doing this analysis and interpreting the information in real-time, that is, when the joint activity takes place, and then using this information to support and guide the users in their activity.

Whenever there is joint activity, the assumption is that there is some activity synchrony visible in the brain activity of the participants. Clearly, a conversation is a joint activity and coordination and nonverbal synchrony, including mimicking, is a well-known phenomenon. As reported in [37], there is also a spatiotemporal coupling of the speaker's and the listener's brain activity. In that particular research fMRI is used to record brain activity, hence, rather far away from the multi-brain game applications we have in mind. Nevertheless, the results support our idea that brain activity from different persons can be measured, analyzed and integrated in order to be used as a source of information to guide behavior and to control or adapt an environment in which the persons perform their activity. As is the case in other research on speaker-listener synchrony, the tighter the coupling between activities, the more successful is the joint task. This neural coupling between two interacting subjects is studied at many places, both with fMRI and EEG, for example at New

York University, in cooperation with the artist Marina Abramovic [5] and at the German Max Planck Institute (Müller and Lindenberger [25]. As a possible application of such research, can we off-line improve the conditions that lead to more synchrony in an interaction? How do we model a social robot or an embodied agent (avatar) such that its awareness of this synchrony can be used to have real-time adaptation of behavior?

There are already many examples of artistic applications where at least one of the cooperating participants contributes by giving the system access to his or her brain signals. In the previous section we looked at some of these early (multi-brain) research and artistic activities. Nowadays, more than 40 years later, we have cheap and commercially available headsets. Moreover, we have the possibility to embed (multi-brain) BCI in multimedia environments that offer audio, visualizations, haptics, and animations without extreme efforts or costs. Also, there is growing interest in computer generated entertainment, meaning the BCI and human-computer interaction researchers turn to artistic and entertainment applications and artists find it more easy to use this available technology to express their ideas. We mention a few examples.

In [23] 'Let me Listen to your Brain' is introduced. It is a project on collaborative music composition where EEG is used to get information about the affective state of one of the collaborators. Musical phrase selection while composing music, but now with possibly two users that control different aspect of a composition using their brain signals is discussed in [6]. In [21] we have four musicians (a violinist, a flautist, a cellist, and a 'brainist'), where during the performance the brainist delivers drone sounds by re-experiencing emotions (classified by EEG) that has been associated with the sounds during a training session. In [19] the MoodMixer system is introduced. Here we have two participants, each wearing an EEG headset with which relaxation and sustained attention is measured. This information is used to position each of them on a two-dimensional audiovisual musical interface, the x-axis for relaxation, the y-axis for attention (see also Fig. 12.1). Changes in the

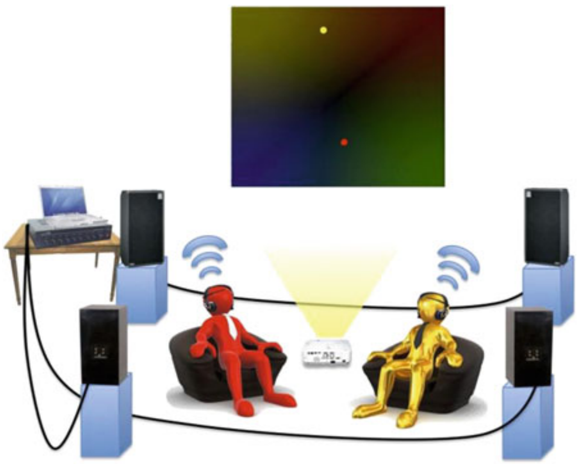


Fig. 12.1 MoodMixer (Image courtesy Grace Leslie and Tim Mullen, University of California, San Diego)

cognitive states of the participants lead to changes in the audiovisual landscape. Participants can try to learn to control these cognitive states and then define little games and they can cooperate to achieve certain effects or composition lines. Sound samples and visual flashes can also be triggered by eye blinks. In principle, more participants, also wearing EEG headsets, can be added to the system.

More players that actively contribute to a music performance through their brain control are present in the Multimodal Brain Orchestra (MBO) presented in [18]. This orchestra has four performers and a conductor. Two of the four performers can use P300 to trigger emotionally classified discrete sound events. Two other performers use SSVEP to modulate articulation and accentuation of an earlier recorded MIDI sequence. The conductor uses a WII-mote as a baton and can decide when the sound events have to be triggered and he can decide about tempo modulations. Hence, evoked brain activity from different performers is directed by the conductor. There is feedback from the music and visualization.

Using knowledge about a collective mental state of an audience may lead to audience participation in entertainment and artistic events. As an example we mention DECONcert, performed in 2003 at the University of Toronto, where 48 people's EEG signals were used to affect a computationally controlled soundscape [22]. Hence, we can think of BCI as an audience participation technology. Other performance arts events in which multi-brain BCI was used are also reported in this paper, including a communal bathing experience in which water waves, sound waves and brain waves were integrated (Fig. 12.2).

Another performance arts example is [8]. Off-the-shelf BCI headsets for mobile users are used to measure audience response to live events and performances. This information can be used to adapt performances to changes in response. This can be

Fig. 12.2 Water waves, sound waves, and brain waves (Reprinted from [22]

done autonomously, but such information can also be provided to, for example, a DJ or VJ who then adapts his or her performance to the audience response [9].

We can focus a little more on multi-party or team activity. What kind of brain activity can we detect and integrate when we have a team of ‘players’ (not necessarily players in a game, but, more generally, persons involved in a joint activity). Can we get information about progress (successful collaboration) and use this information to improve conditions for such team activity? And, as a next step, based on real-time analysis and integration, being able to support and improve the joint activity? For example, during a meeting, can we decide and make group members aware that there is a convergence or divergence of opinions? In a multi-user game with participating teams, and when obtained real-time, such information can certainly help to win the game. Clearly, game, entertainment and artistic environments can be designed in such a way that each kind of combination of one and more persons, individual and joint voluntary control of brain activity and other, not consciously produced brain activity, can be used to play a role during game play.

Chris Berka and her colleagues [38] have a research program that aims at studying team cognition using BCI. They use wireless EEG headsets to measure attention, engagement and mental workload of the members of a team that has to play a serious game: a submarine piloting and navigation simulation. The aim is to achieve measures of the quality of the team performance and use these measures to adapt and rearrange tasks and responsibilities for more optimal team performance. At this moment this adaptation and rearrangement is not done in real-time. In a multi-user entertainment game such information can also be used to remove team members or to rearrange tasks among team members for a next game session. But obviously, real-time adaptation would be much more useful.

In this example (Stevens [38], team members do not manipulate their brain activity. Brain activity is monitored; hence we have a passive multi-brain BCI application. Rather than monitoring one individual engaged in a task, a group of collaborating persons (the team) is monitored with the aim to achieve and maintain ‘neurophysiologic synchrony’ (a positive team rhythm). While in this case the team effort concerns a serious game (a simulation of a critical real-world situation), the application could as well be a multiplayer entertainment game with competing teams and where optimal team performance is a goal as well. Being able to improve, in real time, decision processes by measuring and aggregating activity of all the brains of people involved in the decision making, as can be the case in multi-user games that allow the forming of teams, makes it also possible to issue commands to a game as the result of volatile team brain activity. We will return to this in later sections of this chapter.

12.3 Competition and Collaboration Using BCI

Competition and collaboration are important characteristics of games. For that reason we now look at research in which BCI is studied from a competition and collaboration point of view. Other characteristics of games and how they relate to

BCI can be found in [11]. A viewpoint in the examples that we discuss in this section is that at least two players are involved. And that at least one of them has his or her brain activity measured and it plays a role in the game. This can be to control the game (active BCI) or to adapt the game (scenario, levels, and environment) to the user. In the latter case the user does not consider these game changes as unnatural and is not necessarily aware (and hence does not try to influence it) that game changes are caused by his or her brain activity.

As a side note, notice that we consider these issues in the context of human-*computer* interaction. Hence, one of the partners involved in a game may as well be an artificial agent (physically or virtually embodied agent, e.g., a social robot or a virtual receptionist) or the environment or a device that acts and is supposed to interact in a humanlike way. As an example we can mention the study of [40] where a humanlike robot teacher has access to the brain activity (attention/level of engagement) of a student and adapts his behavior to this activity by raising his voice or have more expressive gestures. In a competitive game environment knowledge about brain activity of a human opponent may give an unfair advantage to such an artificial agent. But that is also the case in a competitive game where a human player has access to the (interpretation of) brain signals of a competitor without having his own brain activity being exposed.

Obviously, when more than one person is involved in a BCI game, the social setting will have impact. Are players co-located or distributed? Is there an audience? What does the audience see and is there interaction between audience and players? In [29] the aim of the research was to investigate the use of BCI in a social setting (a small group of friends or relatives) and in particular the presence and the role of bodily actions of one of the group members playing a simple commercial BCI game while others are watching. In this game the BCI control is obtained from brain activity related to relaxation and concentration. Players used bodily actions (gestures, gaze, and facial expressions) to achieve a desired mental state. But they also used bodily actions to indicate their thoughts to the spectators in the group.

Interactions between co-located BCI gamers have been studied in [12]. We designed a game for research purposes: Mind the Sheep! (MTS!). It can be implemented as a single-player game, a cooperative multi-player game and, although we didn't experiment with that, a competitive multiplayer game. Moreover, it allows both BCI and non-BCI play for players. In our study we introduced a two-player cooperative version of this game to study social interaction between players. Both co-located players wear an EEG cap. The game visualization consists of a 2D map that contains simple representations of a meadow, a sheep pen, dogs and sheep. Players select and move dogs around to herd and eventually fence the sheep in. A dog can be selected with BCI (SSVEP evocation). The players can cooperate through gestures (see Fig. 12.3) and speech to develop and execute a joint strategy. But of course, they see also at the screens what actions the other player takes. There is no integration of brain signals. If one player stops, the other can continue but may take more time to finish the task.

It is more usual to have two-player games where the players compete, each player volitionally using his or her brain activity to compete. This competition point of view,

Fig. 12.3 Two gamers cooperating while playing Mind the Sheep!

where only BCI as input modality to a game is used, can be illustrated with two more examples from earlier research. Consider a BCI version of the well-known Pong game, a virtual tennis game that can be played by two gamers that control their bats (up and down) to hit a tennis ball back to their opponent. Motor imagery (imagine hand movements) has been used to implement a BCI version of this game [16]. That is, individual motor imagery controls the bats, but there is no processing that looks at —or compares—the brain activities of the individual players.

This is different in what was probably the first competitive BCI game, Brainball (Hjelm et al. [14]. In this game we have two players competing. They are expected to compete by relaxing and their performance is measured by EEG. The player who is the best in relaxing wins. The game is made more interesting by visualization of the players' performances that control a ball moving on a table between the two players, seated at opposite ends of the table. This visualisation has impact on their performance and makes the game also attractive for an audience that can decide to support or disturb relaxation of a player. Clearly we need real-time BCI measurement and control of this rolling ball. Brain activity of the players is compared and the difference determines the direction of the ball (moving into the direction of the player who is less relaxed). Hence, this is a different kind of competition, from the point of view of processing brain activity, than in the BrainPong example.

There are of course more examples where players manipulate their brain activity in order to play a particular BCI game. Our interest is in games where players have to compete or collaborate to play a certain game using brain activity. For example, in a two-player game players have to relax to issue a command, for example, to fire a gun at their opponent in a 'Mexican Stand-off. But certainly, being able to look at and experience the performance of their opponent, a gamer can try to increase his or her performance by comparing it with the performance of the opponent. Depending on the visualization or other information communicated to the gamers, such a stand-off game can be compared with a relaxation-based BrainPong game.

Very interesting and certainly a nice example of a multi-brain game is "BrainArena" [3]. It very much illustrates, in a simple setting, some of the ideas mentioned above. It is a simple football game with a ball and goalposts displayed on a screen in front of the two players. There exist two versions of the game, a collaborative and a competitive one. The players wear EEG caps and use motor imagery (imaging left or right hand movement) to get the ball rolling in the direction of the goalposts. In the competitive version their actions are opposed and the player with the best performance wins, in the collaborative version the brain activities are merged and players steer the ball in the desired direction. Hence, in the competitive version it can be seen as a motor imagery version of the earlier mentioned BrainBall game. It can also be compared with a motor imagery version of BrainPong, but in that case each player has its own object (a bat) to control, while in BrainArena they compete to control an object (the ball).

Less obvious is a cooperative two-player game where one player's brain activity is used to support the second gamer in his or her task. This second gamer does not necessarily use BCI. In [32] the authors look at games where players have different roles. One player is physically active while a second player uses his or her mastery of brain activity to provide favorable conditions for the performance of the first player. As mentioned in that paper, new games can be designed where a player's (traditional) game controller input can be modulated by collaborating BCI input, or where game activity is modulated by joint authority over game control input. Clearly, this includes a situation where brain activity of both players is measured and used in the collaborative control of a game. But it also allows games where there is competitive control over a game object. The authors introduce a Multi-User Video Environment (MUVE) that has been designed with both cooperation and competition in mind. Brain activity of one or more players can be used to disturb the physical control input of an opponent or opponents (or the other way around) and competition can be based on BCI input only. In Fig. 12.4 this work is illustrated with a FPS (First Person Shooter) game, where one player is using a Wii Zapper and brain activity of the second gamer controls the steadiness of the crosshairs.

Fig. 12.4 Brain support from one player for the player using the Wii Zapper in a FPS (Image courtesy Chad Stevens, NASA Langley Research Center)

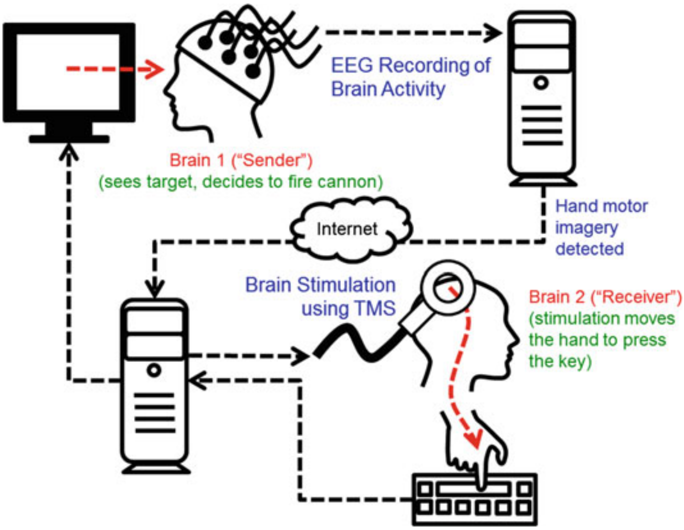


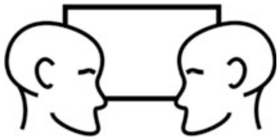
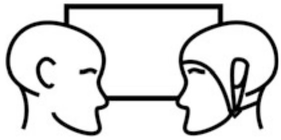
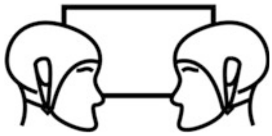
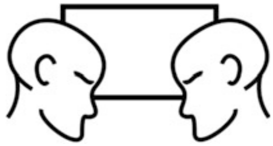
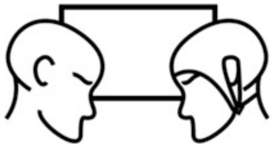
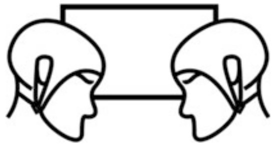
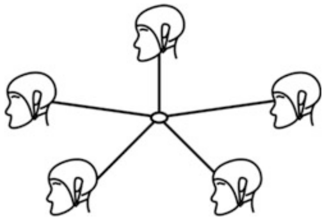
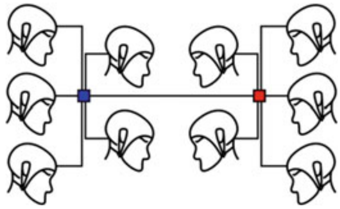
Fig. 12.5 Brain-to-brain communication for games (Image courtesy of R. P. N. Rao and A. Stocco, University of Washington)

Maybe even more interesting is a situation where we translate EEG recordings of brain signals from one gamer to a brain stimulating pulse for a collaborating (or maybe even a competing) gamer. A pilot study on this brain-to-brain communication is presented in [33]. In this study one gamer ("the Sender") uses motor imagery (right hand movement) when a canon has to be fired to destroy a rocket. However, this action is delegated to a second gamer ("the Receiver"). The brain signals of the sender are detected and when recognized as motor imagery, over the internet transmitted and translated to a transcranial magnetic stimulation (TMS) pulse to the left motor brain region of the Receiver. This causes an up-down movement if the hand of the Receiver which results in pressing the "fire" key on the keyboard. In Fig. 12.5 we have illustrated the Sender-Receiver communication.

EEG monitoring of brain activity in order to make decisions about brain stimulation is of course not new. In fact, commercial hardware is entering the market where wireless recording and stimulation are integrated in the same headset. This offers the possibility that multiple players have access to each other's brains, not only to detect and interpret brain activity, but also to stimulate brain regions in order to get certain tasks done or to prevent certain tasks to be done.

In Table 12.1 we have collected the various ways gamers can use BCI. Clearly, brain stimulation as discussed above can be an added parameter to these possibilities. In Sect. 12.5 (Table 12.2) we have more examples of BCI game and team activity situations that are illustrated by one or more of the figures in Table 12.1.

Table 12.1 Various ways of competing and collaborating with and without BCI caps

 Two (or more) players collaborating in a cooperative game. No BCI input	 Two (or more) players, collaborating in a cooperative game. One player uses BCI
 Two (or more) players, collaborating in a cooperative game. Both players use BCI	 Two (or more) players, competing in a competitive game. No BCI input
 Two (or more) players, competing in a competitive game. One player uses BCI	 Two (or more) players, competing in a competitive game. Both players use BCI
 Online collaboration using BCI	 Two competing teams using BCI: blue team (left) versus red team (right)

12.4 More About Multi-brain Games

We now have seen various possibilities for BCI input to games where players compete or collaborate. Usually this concerns two players, but suggestions that involve generalizations to more players are sometimes given. Moreover, the social setting of a game and associated social interactions emerged as an interesting research issue.

Interestingly, in what appears to be the oldest BCI game (BrainBall), there is a volitional contest by both players to control the same object in the game. In the other examples players use their brain activity to perform their own task in a collaborative or competitive game (MTS!, BrainPong), or they try to influence (in a collaborative or in a competitive way) the performance of the other player (MUVE). More subtleties in these distinctions can be introduced, e.g. by looking at dimensions such as social interaction and audience involvement and the role of passive

Table 12.2 A survey of multi-brain games and multi-brain team activities

Game or application	Description	Competition and cooperation
BrainBall (Hjelm et al. [14]. Two players, sitting at opposite ends of a table. On the table is a steel ball that can roll along a magnetic strip on the table	The ball rolls away from the player who is most relaxed. Or, the other way around, to the player who is most stressed. The brain activity of the two players is also visualized on a screen. Often there is a noisy audience	In the competitive mode players compete in relaxation. A player loses when the ball reaches his table edge. In the cooperative mode the players keep the ball in the center or keep it moving from one edge to the other
BrainPong [16].Two players. Pong is a virtual tennis game where key-board keys (up/down) are used to move a bat. A simple 2D virtual environment, displaying the bats of the two players and the ball moving between them is required	A player has to move a bat upwards or downwards in order to return a ball hit by his opponent. This has been done using different BCI paradigms: measurement of stress and relaxation, motor imagery, evoked potentials and ERP's	The game is competitive and turn-taking. No fusion or comparison of brain activity. Players can anticipate actions and make decisions based on this anticipation. The game has been played in noisy environments
BCI Connect Four [20]. In the traditional 'Connect Four' game two players take turns in choosing columns in a 6 (rows) to 7 (columns) matrix where to drop coins. The players' aims are to get 4 own coins connected, before the other does	The 'odd-ball' paradigm using visual flashing of the columns is used to have gamers choose a particular column in the matrix. Nine EEG sensors are used in the centroparietal and occipital regions	This is a competitive game. During a turn an opponent can also try to interfere with the brain activity of the other player by trying to disrupt a choice. There is simultaneous use of BCI and fusion (comparison) of brain activity to decide a winner
BrainArena [3]. Two goals are displayed on a screen; a ball is displayed between them. Players have to steer the ball to one of the goals	Motor imagery (movement of the hands) has to be used to steer the ball in a goal. Eight EEG channels located around the right and left motor cortices. Obviously, such a game can be played in a solo, collaborative and competitive mode	In the collaborative mode the players want to score in the same goal; their brain activity is summed. In the competitive mode players have to score in the opposite goals, hence, the strength of their brain activity is compared to determine the winner
MUVE (Multi-User Virtual Environment, introduced in [32], allows the implementation of multi-user games where physiological information is used to modulate a player's physical activity	MUVE has been shown to provide a gamer's physiological information (including EEG information) to a first person shooter game in order to increase crosshairs steadiness of a Wii Zapper	Relaxing or concentrating can support a main player's performance (cooperative mode) or decrease his performance (competitive mode)
Space Navigation [31]. Users are asked to navigate a spacecraft (in a simulator) and pass a planet as close as possible	Spaceship control is done using a ring around the spaceship. 8 Positions are distinguished, representing directions in which to steer. Circles in turn flash allowing a P300 target choice	Two players cooperate in joint pointer control. Early fusion (averaging of the ERP input) and late fusion (averaging the individual pointer movement decisions) are considered

(continued)

Table 12.2 (continued)

Game or application	Description	Competition and cooperation
MTS! [12] is a video game that allows two co-located players—using multi-modal input—to command dogs to certain positions on a virtual meadow in order to herd sheep inside a fence	SSVEP is used to choose one of the dogs that has to chase the moving sheep. There is a trade-off between being certain that SSVEP is successful and being able to start chasing the sheep	Depending on the version gamers can collaborate using various combinations of input modalities, including BCI. There is no fusion of their modalities, but they see each other's actions
Assess the quality of the performance of a submarine piloting and navigation team. Rearrange team or tasks when necessary [38]	EEG monitoring of engagement, workload and alertness using 9-channel wireless headsets	Team members can have different tasks. Speech interaction between team members
Online collaboration in a perceptual decision task [7]	On-line collaboration of a group of 20 subjects to distinguish, using ERPs, car and face images	No interaction between subjects. Fusion is done at a decision level using voting procedures
Collaboration in a movement planning task [42]. Decide about movement and plan a visually guided right-hand reaching task	Group of 20 subjects. Three different methods for fusing EEG information: ERP averaging, feature concatenating, and voting	No interaction between subjects. In this case the voting method (fusion on decision level) turned out to be optimal
Online collaborative decision making in a visual target decision task (Yuan et al. [44])	Groups of 6 participants. Decide between face images (Go tasks) and car images (NoGo tasks). Single-trial EEG-based decision making by averaging ERPs	No interaction between subjects. Experiments suggest that collaborative BCI can accelerate reliable decision making in real time
MultiMind [39]. Aggregate biometric information from a number of individuals for joint decision making for (potential) security-related applications	Two subjects wearing Emotiv Epoc headsets. They watch a sequence of slides with humorous content and their emotional response is fused to obtain a collected assessment of the presented information	No interaction between subjects. Although the approach is called multibrain signal fusion, it seems that fuzzy logic is used to fuse information about the subjects' facial expressions collected by the headsets

BCI in these games. And, of course, we need to look at the consequences of having more than (just) two players involved in multi-party and multi-brain games.

When looking at a possible definition of multibrain computer interfacing it now should be clear that it is unwise to be restrictive. Clearly, two or more persons need to be involved. Brain activities of two or more persons have to be integrated in the application. But, not necessarily at the same time and not necessarily in a synchronous way. In traditional multimodal interaction research we have one person interacting with an application using different modalities. The modalities can complement each other and fusion of the different modalities helps to solve ambiguities and can lead to more robustness. Usually three levels of fusion are distinguished, the data level, the feature level and the decision level. Fusion is meant to make the interaction effort stronger, to make clearer what is intended by an individual user.

We can also speak of fusion at different levels in the case of a cooperative game. For example brain activity of two or more players can be combined to have them make a particular decision in a game or to have them lift a spaceship in a virtual game environment, a task that would have been much more difficult if only brain activity of one player could be used. This is not some peculiar property of the brain activity modality. Lifting hand and arm gestures, facial expressions, or gaze behavior of two or more gamers could be implemented to have the same result. Or, any combination of different modalities that are used by different persons in a joint effort.

In the case of brain activity, comparable brain activity seems to be the most obvious first choice for data level fusion. But that may change in the future when we learn more about dependencies between different BCI paradigms. In a cooperative game situation fusion at the level of decision making can mean making a joint decision or doing a joint activity, but it can also mean a division of labor where players take responsibility for subtasks that help in reaching their joint goal.

Also in a competitive game where two or more persons are involved we can talk about fusion of information coming from different modalities and coming from different participants. Again, for the sake of discussion, let us focus on the brain activity modality. When we have competing players, rather than 'adding' information, on whatever level, we let the system (interface, game) compare ('subtract') information and make decisions that benefit the 'winner' or 'winners' who have outperformed with their joint brain activity the losers. Deciding when and how a team of BCI gamers has outperformed another team for deciding about or doing a particular activity can again be done at the data, feature and decision level. However, it should be mentioned that at each level different information is available to guide decisions. As an example, at the decision level we can use common sense and domain knowledge and we know about methods from artificial intelligence research that help us to represent and to reason about such knowledge. At every level of fusion, methods are available that take into account level context.

All these observations make it more difficult to get closer to a definition of multibrain games. Or, less difficult, to a decision that we should accept that there cannot be one definition and that multibrain games are just games in which measured brain activity of two (or more) gamers can be used to control commands or will be used to adapt a game to its users. Fusion of modalities of one user is an issue, but also fusion of modality information coming from different users (competing or collaborating) is an issue. There is another issue, when we talk about fusion, who is taking care of it? In traditional human-computer interaction a multisensor system provides input to computing power and intelligence that makes decisions. In games, but not only in games, human decision making can also be used to decide about how to integrate and fuse information, including brain activity information, coming from different modality sources and from different users and made available to a human decision maker or (game) team leader. In fact, in the Multimodal Brain Orchestra (see Sect. 12.2.2) it is the human conductor that makes decisions about the fusion of the classification results obtained from the EEGs (SSVEP and P300). In this example there is, if we understand it well, no ‘adding up’ or otherwise processing of joint activity at the level of brain signals or features extracted from brain signals.

Having now discussed the different ways brain activity from two or more sources can be integrated (without claiming completeness), we now look at research that has been done in the past and that supports our ideas about having multibrain BCI games in the near future by demonstrating that brain activity of multiple persons can be used in applications. Some examples, not really aimed at collective decision making or performing an action through collective brain activity were already mentioned in Sect. 12.2. We already mentioned team cognition [38] and audience response and participation using BCI [8, 22].

Game applications of this audience response can be thought of, but even more interesting is being able to improve, in real time, decision processes by measuring and aggregating activity of all the brains of people involved in the decision making process, as might be the case in multi-user games that allow the forming of teams. Teams allow some kind of ‘collective wisdom’ to make decisions. Real-time decision making by a team of users rather than an individual user has been investigated in [7]. In this research twenty users had to make perceptual decisions, that is, deciding when confronted with a series of pictures whether a particular picture was a face or a car. Prediction of a decision based on aggregated (ERP) brain activity turned out to be possible and, compared with an individual user, both the decision accuracy and decision speed could be improved. Collaborative classification of visual targets, but now using visually evoked potentials (VEPs) was also investigated in [43]. Clearly, applying such research results in a multi-player game context can make those games more interesting to play.

Collaborative brain-computer interfaces have also been studied by Wang and colleagues [42]. It is investigated how EEG data from twenty users can be used to predict and decide about the planning of movements. Clearly, as they mention, this is the kind of information that can be used in a multi-player game that allows the forming of teams and can have team performance included in the game, rather than just have input from individual players only.

12.5 Distinguishing Multi-brain Games

In Table 12.2 we have collected the characteristics of many of the games and systems we discussed above. Some systems not discussed above are also included in the table [20, 31, 39, 44].

12.6 Discussion

We discussed the use of BCI as an input modality in a multiparty context and the various ways brain activity can be integrated in game contexts. We focused on integrating brain activity from multiple persons. It is clear that many problems related to BCI in general have to be attacked. It can also be concluded, as we did in [26], that it nevertheless is possible to design multiparty games in which multi-brain activity is included, and that it can be done in such a way that it introduces interesting challenges to the gamers (and the designers), rather than assuming that no efficient or robust use can be made of this technology. In the context of games, entertainment and artistic applications robustness and efficiency are not the right keywords.

We discussed multi-brain applications from the viewpoints of competition and collaboration. There is a growing number of BCI games where indeed we have competing and collaborating gamers. The games are simple and although they are fun to play, until now this is only done in research environments. Moreover, in these cases BCI is not integrated in a game context where other modalities play an important role, except for the MTS! game, but in that case the BCIs of the gamers are not integrated, and the Wii Zapper game, but there only BCI is used for one of the gamers. But we certainly can expect that in future research more complex multi-brain games will appear. And adding brain stimulation to the many situations we already distinguished will increase the possibilities to introduce challenging multi-brain games enormously.

Also the research and applications that tell us about the fusion of brain activity of more than two persons, and even from tenths of persons to make group decisions or adapt the game, a performance or an environment to group preferences or changes in cognitive state or emotions give us a view of the future where we can have multi-brain applications in a MMORPG (Massively Multiplayer Online Role-Playing Game). Many of these games assume gamers to form teams that can compete or collaborate. Team decisions or team leader's decisions in a MMORPG can be based on collective thoughts of a team or a sub team. Obviously, synchrony of thoughts is a problem here. However, natural game events can trigger joint and synchronized event related brain activity among team members. The potential role of 3rd party team communication software such as TeamSpeak should be considered. And again, perfectness would be unnatural. A 'synchronized kill' in the "Ghost Recon, Future Soldier" game does not have to be perfect. Joint brain and synchronized brain activity can be triggered because of various artificial stimuli that are designed in the game. There can be natural moments to take an explicit vote on how to continue or make an otherwise important decision. But fast decision making based on merging of brain activities of a large team, accepting that not yet everyone in the team is ready for it or agrees with the majority, is also natural.

However, such observations should not be confined to a video game situation with multiple users only. For every video game situation we can find a serious game situation where trainees have to learn to make decisions and the serious game environment should have models that allow predicting, anticipating and processing different ways of EEG information coming from multiple sources. Serious game environments train for real applications.

There are lots of context issues that we are aware of or that we are made aware of when we participate in more traditional interfaces that allow collaborative or—less common—competitive activities. So we should look at what it means, in a brain-computer interface situation, what impact it has when we are aware of others' actions and intentions, how we perceive this awareness, what kind of feedback do we get on our contribution to a collaborative or competitive activity and what kind of control do we feel about our possibility to contribute [45].

12.7 Conclusions

In this chapter we surveyed the state-of-the-art of research in applications where the applications require input from multiple persons and where at least for one person input from a BCI is obtained. One may think of applications where users compete or collaborate, but also applications where input collected from different individuals is processed and made visible or audible in art performances.

This view on the use of BCI raises interesting questions. It is only recently that in BCI research interest emerged in looking at integrating or making use of different BCI paradigms in one application for one individual user. The example individual user used to be a disabled person not being able to communicate or control by using his or her muscles. However, users without such disabilities can move around freely, can gesture, can speak and have meaningful facial expressions. These display information—intended or unconsciously—that can be interpreted and that complement information obtained from the interpretation of brain signals, or the other way around, knowing about an interpretation of brain signals can support other communication modalities. There needs to be a fusion of information at the level of signals (when possible), features or decisions. Clearly, this requires quite a different research approach than is usual in traditional BCI research that is focused on signals coming from a particular region of the brain and that preferably should not be disturbed by any other brain activity at all.

In this chapter we looked at the situation where the information that is obtained in the human-computer interface and that is communicated to the application did come from different persons. The application can have input from users looking at one particular modality only—for example, for all users there is integration of their brain signals—or different users provide information to the application that is coming from different interaction modalities—for example, the physiological information from one user is used to modulate the BCI command signals from a second user. Clearly, giving all possible input modalities, combinations of input modalities, and voluntarily expression and involuntarily releasing of information through these modalities, it should be clear that more insight need to be acquired about this fusion of information, whether it is on the signal level (source signals associated with different activity modalities), feature level, or decision level. In addition, from the point of view of applications, we need to experiment with applications where this fusion is guided by characteristics of the users, the context and the kinds of applications.

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References

1. Allison, B.Z., Dunne, S., Leeb, R., del Millan, J.R., Nijholt, A.: Future BNCI: a roadmap for future directions in brain/neuronal computer interaction research. In: DG Information Society and Media (Directorate "ICT Addressing Societal Challenges", Unit "ICT for Inclusion") Under the Seventh Framework Programme [FP7/2007-2013] of the European Union. http://bnci-horizon-2020.eu/images/bncih2020/FBNCI_Roadmap.pdf. Accessed 5 June 2014
2. Azar, A.T., Balas, V.E., Olariu, T.: Classification of EEG-based brain-computer interfaces. In: Iantovics, B., Kountchev, R. (eds) Advanced Intelligent Computational Technologies and Decision Support Systems, Studies in Computational Intelligence, vol. 486, pp. 97–106. Springer, Heidelberg (2014). doi: 10.1007/978-3-319-00467-9_9
3. Bonnet, L., Lotte, F., Lécuyer, A.: Two brains, one game: design and evaluation of a multi-user BCI video game based on motor imagery. IEEE Trans. Comput. Intell. AI Games **5**(2), 185–198 (2013)
4. Brunner, C., Blankertz, B., Cincotti, F., Kübler, A., Mattia, D., Miralles, F., Nijholt, A., Otal, B., Salomon, P., Müller-Putz, G.R.: BNCI Horizon 2020—Towards a Roadmap for Brain/Neural Computer Interaction. In: Stephanidis, C., Antona, M. (eds.) Universal Access in Human-Computer Interaction (UAHCI 2014), 8th International Conference, Heraklion, Crete, Greece, June 2014. Lecture notes in computer science, vol. 8513, pp. 475–486. Springer, Heidelberg (2014)
5. Dikker, S.: Neuroscience experiment I: measuring the magic of mutual gaze. (Real-time interactive neuroimaging art installation). In: Collaboration with Marina Abramovic, Matthias Oostrik, and Representatives of the Art and Science: Insights into Consciousness Workshops, The Watermill Center, New York. http://www.youtube.com/watch?v=Ut9oPo8sLJw. Accessed 5 June 2014
6. Eaton, J., Miranda, E.R.: Real-time notation using brainwave control. In: Bresin, R. (ed.) Proceedings of the 2013 Sound and Music Computing Conference, pp. 130–135. Stockholm, Sweden (2013)
7. Eckstein, M.P., Das, K., Pham, B.T., Peterson, M.F., Abbey, C.K., Sy, J.L., Giesbrecht, B.: Neural decoding of collective wisdom with multi-brain computing. NeuroImage **59**(1), 94–108 (2011)
8. Fan, Y.-Y., Myles Sciotto, F.: BioSync: an informed participatory interface for audience dynamics and audiovisual content co-creation using mobile PPG and EEG. In: Proceedings 13th International Conference on New Interfaces for Musical Expression (NIME), pp 248–251. KAIST, Daejeon, Korea, May 2013
9. Gates, C., Subramanian, S., Gutwin, C.: Djs' perspectives on interaction and awareness in nightclubs. In: Carroll, J.M., Coughlin, J. (eds.) Proceedings of the 6th Conference on Designing Interactive Systems, ACM, pp. 70–79, June 2006

10. Gürkök, H., Nijholt, A.: Brain-computer interfaces for multimodal interaction: a survey and principles. Human Comput. Interact. **28**(5), 292–307 (2012)
11. Gürkök, H., Nijholt, A., Poel, M.: Brain-computer interface games: towards a framework. In: Herrlich, M., Malaka, R., Masuch, M. (eds.) Proceedings 11th International Conference on Entertainment Computing (ICEC 2012), Lecture Notes in Computer Science, vol. 7522, pp. 144–157. Springer, Heidelberg (2012)
12. Gürkök, H., Nijholt, A., Poel, M., Obbink, M.: Evaluating a multi-player brain-computer interface game: challenge versus co-experience. Entertainment Comput. **4**(3), 195–203 (2013)
13. Hasson, U., Landesman, O., Knappmeyer, B., Vallines, I., Rubin, N., Heeger, D.J.: Neurocinematics: the neuroscience of film. Projections **2**(1), 1–26 (2008)
14. Hjelm, S.I., Browall, C.: Brainball: using brain activity for cool competition. In: Proceedings of the First Nordic Conference on Computer-Human Interaction (NordiCHI 2000), Stockholm, Sweden (2000)
15. Kamiya, J.: Conscious control of brain waves. Psychol. Today **1**(11), 56–60 (1968)
16. Krepki, R., Blankertz, B., Curio, G., Müller, K.R.: The Berlin brain-computer interface (BBCI)—towards a new communication channel for online control in gaming applications. Multimed Tools Appl. **33**(1), 73–90 (2007)
17. van de Laar, B., Gürkök, H., Plass-Oude Bos, D., Nijboer, F., Nijholt, A.: User experience evaluation of brain-computer interfaces. In: Allison, B.Z., et al. (eds.) Towards Practical Brain-Computer Interfaces: Bridging the Gap from Research to Real-World Applications, pp. 223–237. Springer, Heidelberg (2012)
18. Le Groux, S., Manzolli, J., Verschure, P.F.M.J., Sanchez, M., Luvizotto, A., Mura, A., Valjamae, A., Guger, C., Prueckl, R., Bernardet, U.: Disembodied and collaborative musical interaction in the multimodal brain orchestra. In: Conference on New Interfaces for Musical Expression (NIME 2010), pp. 309–314 (2010)
19. Leslie, G., Mullen, T.: MoodMixer: EEG-based collaborative sonification. In: Jensenius A.R., Tveit, A., Godøy, R.I., Overholt, D. (eds.) In: Proceedings 11th International Conference on New Interfaces for Musical Expression (NIME), pp. 296–299. Oslo, Norway (2011)
20. Maby, E., Perrin, M., Bertrand, O., Sanchez, G., Mattout, J.: BCI could make old two-player games even more fun: a proof of concept with "Connect Four". Adv. Human Comput. Interact. **2012**(124728), 8 (2012)
21. Makeig, S., Leslie, G., Mullen, T., Sarma, D., Bigdely-Shamlo, N., Kothe, C.: First demonstration of a musical emotion BCI. In: D'Mello, S., Graesser, A., Schuller, B., Martin, J.-C. (eds.) Proceedings of the 4th international conference on Affective computing and intelligent interaction (ACII'11), Part II. Lecture notes in computer science, vol. 6975, pp. 487–496. Springer, Heidelberg (2011)
22. Mann, S., Fung, J., Garten, A.: DECONcert: making waves with water, EEG, and music. In: Kronland-Martinet, R., Ystad, S., Jensen, K. (eds.) Computer Music Modeling and Retrieval, 4th International Symposium, CMMR 2007. Lecture notes in computer science, vol. 4969, pp. 487–505. Springer, Heidelberg (2008)
23. Mealla, S., Väljamäe, A., Bosi, M., Jordà, S.: Let me listen to your brain: physiology-based interaction in collaborative music composition. In: CHI 2011 Workshop paper, pp 1–4 (2011)
24. Mühl, C., Chanel, G., Allison, B., Nijholt, A.: A survey of affective brain computer interfaces: principles, state-of-the-art, and challenges. Brain Comput. Interfaces **1**(2), 66–84 (2014)
25. Müller, J.V.: Lindenberger U (2012) Intra- and interbrain synchronization and network properties when playing guitar in duets. Front Hum Neurosci. **6**(3), 12 (2012)
26. Nijholt, A., Oude Bos, D., Reuderink, B.: Turning shortcomings into challenges: brain-computer interfaces for games. Entertainment Comput. **1**(2), 85–94 (2009)
27. Nijholt, A., Allison, B.Z., Jacob, R.K.: Brain-computer interaction: can multimodality help? In: 13th International Conference on Multimodal Interaction, Alicante, Spain, pp. 35–39. ACM, NY, USA, Nov 2011
28. Nijholt, A., Gürkök, H.: Multi-brain games: cooperation and competition. In: Stephanidis, C., Antona, M. (eds.) Proceedings Universal Access in Human-Computer Interaction. Design

Methods, Tools, and Interaction Techniques for Inclusion. Lecture notes in computer science, vol. 8009, pp. 652–661. Springer, Heidelberg (2013)
29. O'Hara, K., Sellen, A., Harper, R.: Embodiment in brain-computer interaction. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'11), pp. 353–362. ACM, NY, USA
30. Plass-Oude Bos, D., Reuderink, B., van de Laar, B., Gürkök, H., Mühl, C., Poel, M., Nijholt, A., Heylen, D.: Brain-computer interfacing and games. In: Tan, D., Nijholt, A. (eds.) Brain-Computer Interfaces: Applying Our Minds to Human-Computer Interaction, pp. 149–178. Springer, London (2010)
31. Poli, R., Cinel, C., Matran-Fernandez, A., Sepulveda, F., Stoica, A.: Towards cooperative brain-computer interfaces for space navigation. In: Proceedings of the 2013 International Conference On Intelligent User Interfaces (IUI '13), pp. 149–159. ACM, New York, NY, USA (2013)
32. Pope, A.T., Stevens, C.L.: Interpersonal biocybernetics: connecting through social psychophysiology. Proceedings of the 14th ACM International Conference on Multimodal Interaction (ICMI '12), pp. 561–566. Santa Monica, CA, USA, ACM, NY, USA (2012)
33. Rao, R.P.N., Stocco, A.: Direct brain-to-brain communication in humans: A pilot study. http://homes.cs.washington.edu/~rao/brain2brain/experiment.html. Accessed 5 June 2014
34. Reuderink, B., Poel, M., Nijholt, A.: The impact of loss of control on movement BCIs. IEEE Trans. Neural Syst. Rehabil. Eng. **19**(6), 628–637 (2011)
35. Rosenboom, R. (ed.): Biofeedback and the arts: results of early experiments. Aesthetic Research Centre of Canada, Vancouver (1976)
36. Sobell, N.: Streaming the brain. IEEE Multimedia **9**(3), 4–8 (2002)
37. Stephens, G.J., Silbert, L.J., Hasson, U.: Speaker–listener neural coupling underlies successful communication. Proc. Natl. Acad. Sci. U.S.A. **107**(32), 14425–14430 (2010)
38. Stevens, R., Galloway, T., Berka, C., Behneman, A.: A neurophysiologic approach for studying team cognition. In: Proceedings Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC), pp 1–8 (2010)
39. Stoica, A,: MultiMind: multibrain signal fusion to exceed the power of a single brain. In: Proceedings 2012 Third International Conference on Emerging Security Technologies, PP. 94–98. IEEE Computer Society, Lisbon, Portugal (2012)
40. Szafir, D., Mutlu, B.: Pay attention! Designing adaptive agents that monitor and improve user engagement. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'12), Austin, TX, USA, May 2012, pp. 11–20. ACM, New York, USA (2012)
41. Vidal, J.J.: Toward direct brain-computer communication. Ann. Rev. Biophys. Bioeng. **2**, 157–180 (1973). doi:10.1146/annurev.bb.02.060173.001105
42. Wang, Y., Jung, T.P.: A collaborative brain-computer interface for improving human performance. PLoS ONE. www.plosone.org **6**(5), e20422:1–11 (2011)
43. Yuan, P., Wang, Y., Gao, X., Jung, T.-P., Gao, S.: A collaborative brain-computer interface for accelerating human decision making. In: Stephanidis, C., Antona, M. (eds.) Proceedings Universal Access in Human-Computer Interaction: Design Methods, Tools, and Interaction Techniques for eInclusion. Lecture notes in computer science, vol 8009, PP. 672–681. Springer, Heidelberg (2012)
44. Yuan, P., Wang, Y., Gao, X., Jung, T.-P., Gao, S.: A collaborative brain-computer interface for accelerating human decision making. In: Stephanidis, C., Antona, M. (eds.) Proceedings Universal Access in Human-Computer Interaction: Design Methods, Tools, and Interaction Techniques for eInclusion. Lecture notes in computer science, vol. 8009, PP. 672–681. Springer, Heidelberg (2013)
45. Yuill, N., Rogers, Y. Mechanisms for collaboration: a design and evaluation framework. ACM Trans. Comput. Human Interact. **19**(1), Article 1 (2012)