IEEE Transactions on Computational Intelligence and AI in Games (Special Issue on Brain/Neuronal-Computer Games Interfaces and Interaction), 2013, *in press*.

This paper in IEEE Xplore®: http://dx.doi.org/10.1109/TCIAIG.2012.2237517

Adapting the P300-based brain-computer interface for gaming: a review

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***Abstract*—The P300-based brain-computer interface (P300 BCI) is currently a very popular topic in assistive technology development. However, only a few simple P300 BCI based-games have been designed so far. Here, we analyze the shortcomings of this BCI in gaming applications and show that solutions for overcoming them already exist, although these techniques are dispersed over several different games. Additionally, new approaches to improve the P300 BCI accuracy and flexibility are currently being proposed in the more general P300 BCI research. The P300 BCI, even in its current form, not only exhibits relatively high speed and accuracy but also can be used without user training, after a short calibration. Taking these facts together, the broader use of the P300 BCI in BCI-controlled video games is recommended.**

***Index Terms*—Brain computer interfaces, P300 BCI, games.**

I. INTRODUCTION

THE BRAIN-COMPUTER interface (BCI) is a system that provides an individual with a new, non-muscular pathway for sending messages or commands to the external world [1], [2]. BCIs are usually based on the classification of patterns observed in the user's electroencephalogram (EEG), i.e. noninvasive recording of the electrical potentials generated in the brain. The development of BCI technology is mainly oriented to meet the needs of paralyzed patients who can no longer use their muscles [1], [3], [4] but attempts have also been made to share this technology with additional target groups [4], [5].

BCI-controlled games (primarily video games) constitute an area that may meet the interests of both groups of users, although possibly not in the same way. The paralyzed patients may be interested in such games because these games are the only type they can play for recreational purposes. Additionally, "gaming can be an excellent motivation to spend time with a BCI system in order to achieve better control" [5]. For healthy people, a BCI-controlled game may be attractive as an opportunity to control a computer without movement, merely "with thoughts". These individuals can easily turn to non-BCI games if not sufficiently satisfied with a BCI game. Moreover, a non-paralyzed user can use a BCI not only as an alternative but also as a supplement to existing input devices, such as the mouse, keyboard, joystick, touchscreen, or dedicated gaming controller.

Among the BCIs for non-gaming applications, one of the most popular technologies is the P300 BCI [6], a BCI that primarily utilizes the P300 wave of the brain event-related potentials (ERPs). This BCI presents the user with a screen on which visual events, used as stimuli, appear at distinct locations. The user attends one of these locations and silently counts the events (e.g., flashes) that occur there. The counted or otherwise-attended event (the target event) can be detected because this event is followed by a higher-amplitude P300 than unattended (nontarget) events. A command associated with this location is executed.

In the most typical application, the P300 Speller, the main part of the visual display is a matrix consisting of letters of the alphabet. To accelerate letter selection, rows and columns of letters are flashed rather than single cells. The order of the stimuli is random, which is important to elicit the P300. In most cases, each stimulus is presented at least several times (often more than 10) to improve the signal-to-noise ratio using separate averaging of the data related to each row and column. Preprocessing and feature extraction are applied to the EEG

Manuscript received April 30, 2012; revised September 28, 2012 and November 25, 2012; accepted December 21, 2012. This work was supported in part by the Skolkovo Foundation under Grant 1110034.

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epochs time-locked to the stimuli, and the feature vectors corresponding to known stimuli are then submitted to the classifier. Before actual use of the BCI, the classifier is trained using feature vectors labeled as "target" and "nontarget". To obtain these vectors, a calibration session, in which the user attends the pre-defined locations, should be completed. After the classifier is trained, its output indicates the row and column in which flashes were followed by a brain response best resembling the response to a target stimulus. The letter found at their intersection is then typed [3], [6], [7], [8].

In the case of a P300 BCI game, the user's clearly nonmotor act of attending and noticing events results in actions in the game's virtual world. Acting without actual or imagined movement may be intriguing and attractive due to this experience's divergence from everyday life.

The following P300 BCI features may be specifically important in gaming applications:

(1) The P300 BCI can be controlled with high accuracy (see next item), even without prior user training [9].

(2) The P300 BCI classifier training requires little time. For instance, 72.8% of naпve participants spelled a five letter word with 100% accuracy after only a five minute calibration [9]. In games, an even shorter calibration can be used whenever classifier accuracy is not critical.

(3) Almost all healthy people [9] and many patients, including the severely paralyzed [10]–[12], are able to use the P300 BCI. Typically, no special training is needed to operate this BCI, unlike the motor imagery-based BCI.

The P300 BCI is also one of the fastest among the currently available BCIs, although, in general, BCIs are still slower than normal input devices, such as the mouse or game controllers. For example, in *MindGame* by Finke *et al.* [13] (see below) two seconds were required for single-trial stimulation and collection of the EEG responses. The simplicity of the online data processing allowed for providing feedback, in principle, almost immediately afterward, although it is not clear from the report if this was the case in the actual implementation. A response to a single P300 BCI stimulus can be classified as target vs. nontarget even without knowledge of the responses to other stimuli [14]. Thus, the minimal P300 BCI response time can be nearly as brief as the most discriminative part of a single EEG response, such as approximately 0.5 s for healthy users. Single-trial operation is associated with decreased accuracy, but this is not critical in many cases, since imperfect control can be well integrated into games [15].

Attending the letters or "buttons" for commands to be controlled in the P300 BCI is natural, as people typically attend an item when they plan to act on that item in a normal (physical) way [16]. The same mode of operation is used in another popular BCI, a BCI based on the steady-state visual evoked potential (SSVEP), and in non-BCI input devices based on eye trackers. In contrast to the SSVEP BCI, the P300 BCI does not require concentration on a stimulus flickering at a constant rate, which may cause fatigue and, in certain settings, even epileptic seizures [17], [18]. Compared with eye-gaze input devices, the P300 BCI is less vulnerable to the "Midas touch problem" (triggering unintended commands, for instance, by spontaneous fixations [16]), because it depends on attention, whereas eye trackers rely only on the gaze direction. The P300 BCI can also be used by patients who cannot use gaze-controlled input due to severe paralysis [12].

Unlike the majority of the existing BCIs, the P300 BCI allows easy selection from many (up to tens) available commands in one step.

Surprisingly, however, the P300 BCI is still not popular among the BCI game designers (see, for example, Table 10.1 in [19], which presents games controlled by different BCIs), despite this BCI's high popularity in the field of assistive technology. This difference can likely be explained by considering different motivations for using games and non-gaming applications. Whereas the latter are used because these applications produce certain desired results, games are played for the process of their use, known as gameplay [20]. The unusual experience provided by the BCI technology motivates BCI use in games, and it is possible that the experience of using the P300 BCI has aspects that render this system less attractive than the other BCIs.

Human-computer interaction (HCI) in BCI games have been little studied [19], [21]. Due to the lack of relevant empirical data, a speculative analysis of the P300 BCI may be used to outline factors potentially negatively impacting the user's experience, compared with the experience of using other BCIs:

(1) *Separated stimuli and action.* The P300 BCI user must concentrate his or her attention on stimuli presented at a certain distance from the positions at which the actions occur (i.e., the normal focus of spatial attention in games).

(2) *Simple, static and stereotyped stimuli.* The user of the standard P300 BCI must concentrate his or her attention on unvarying stimuli. The positions of the stimuli related to specific commands do not change. In contrast, in immersive games, the objects on which the user concentrates his or her attention often change or move.

(3) *Goal selection instead of process control.* A BCI game user may expect that the BCI technology allow the continuous and gradual control of movement. Such movement control is impossible with the P300 BCI, which only enables selection from the available commands. In general, such a "goal selection" strategy is currently a significantly more efficient approach to BCI development than "process control" [2]. However, the latter type of control may cause the user to feel that he or she at least occasionally directly controls certain movement in the game's virtual world.

(4) *Repeated stereotyped mental actions required to trigger a single action in the game.* The standard P300 BCI protocol requires that each stimulus (e.g., each row and column) is presented repeatedly and should be normally attended each time the stimulus is presented. Imagine that you have to push a button 15 times in a row (a number often used in spelling protocols, e.g. [9]) to trigger each single action in a game.

(5) *The need to use mental actions unnaturally mapped to virtual-world actions*. Mapping between a mental action and its result, a virtual action, can be easily made intuitive in some

BCIs. For example, in a game controlled by a BCI based on motor imagery, the imagination of left hand movement may make an avatar move to the left [19]. In the SSVEP BCI, an action is triggered simply by attending a target location, without any additional task. In contrast, the P300 BCI requires an individual to count or at least to "note" the events at the attended location. This task is quite different from the mental activity normally associated with actions. The need for such a task, which can be perceived as foreign to gameplay, significantly impedes the use of the BCI [22] and may work against immersion [23].

(6) *The P300 BCI as a "synchronous" BCI.* The P300 BCI user must synchronize his or her mental actions with the events generated by the computer. More specifically, after making a decision to act, he or she must wait for one or several target stimuli and perform mental actions in response to them (e.g., count each stimulus), and the BCI will issue a command only after presenting the stimuli (including the nontargets) and finishing collecting the EEG where the response to the last stimulus is expected. The user's task is therefore rather tiresome, and time between the wish to act and the resulting action in the virtual world depends on the stimuli presentation protocol and can be much longer than its minimal estimates (these estimates were given above). In contrast, "asynchronous" BCIs, which do not require such synchronization [24], provide the user with more freedom and enable a more direct conversion of the user's intention into an action (e.g., a pinball machine control in a motor imagery-based BCI [25]) .

Is it possible to reduce these negative factors apparently associated with the P300 BCI to such an extent that the games controlled by this BCI will attract users? Below, we review the P300 BCI games described in the literature and demonstrate that, in their design, certain solutions have already been developed. We then briefly discuss the current trends in the P300 BCI research, from which further techniques for improving P300 BCI games can be borrowed.

II. EXISTING P300 BCI GAMES

A. From a BCI to a BCI game

People tend to find the experience of BCI control exciting even in experiments that model routine operations, such as typing [26]. Defining a game as "an activity or contest with a goal involving rules in which one or more people engage to have fun" ([27], Table 1), simple games can easily be created using a P300 BCI Speller without changing the interface itself and by just specifying a few rules, such as "a player should type a meaningful sentence without any error; the goal is to type a sentence of maximal length".

This approach was used in our research game [28], which was designed based on the following rationale. We hypothesized that an item linked to a certain command in a P300 BCI that is unwanted or even dangerous in the current situation has an increased potential to attract attention. Even if the user tries to ignore the item, highlighting this item will elicit an ERP resembling the ERP resulting from a target stimulus. The related unwanted command will be then executed. This "dangerous command paradox" was tested using a BCI modeling a control panel of a device. In each trial, one command was indicated as the target and added one point to the user's score if selected. In half of the trials ("dangerous condition"), one command was also indicated as "dangerous" and, if selected, five points were subtracted from the user's score. The frequency of "dangerous" command selection increased in the "dangerous" condition compared with the control condition, but the effect was not significant [28].

Another straightforward approach could be the use of the mainly unmodified P300 BCI to control known turn-based games that do not impose strong time constraints. Indeed, P300 BCI chess games have been occasionally mentioned in the literature (e.g., [29]). In our laboratory, we found it useful to employ chess to test a BCI-controlled 6-DOF robot arm. Involvement of the user into gameplay partly compensates the tediousness of this step-by-step P300 BCI control and renders long experiments possible (Fig. 1).

Fig. 1. An example of playing an unmodified game using a P300 BCI (here, using a BCI-controlled 6-DOF robot arm) for testing purposes.

The P300 BCI was employed to control *Second Life* using specially developed interface masks [30]. It has been proposed that the experience obtained using such virtual-world applications can be helpful in the use of real-world applications [30].

Further integration of the P300 BCI and turn-based games can be done by presenting the stimuli directly on virtual objects. For example, attending flashes on a door can result in its opening, and attending flashes on a stone can turn it into a new character.

However, for the vast majority of games the BCI-mediated control, when used simply as a substitute for traditional input devices, is hardly sufficient to maintain interest during long-term use. Below we focus on attempts to adapt a BCI and a game to each other, which can be a more efficient way of creating truly engaging BCI games.

B. MindGame

In this game [13], the user moves a character from one field to another on a game board. The length of the character's steps depends on the BCI classifier output, with a stronger brain response to target flashes leading to larger steps and the faster attainment of the game goal, which is to visit all predetermined target fields. Unlike for typical P300 BCI spellers, the stimuli are not presented group-wise (as in rows and columns) but rather separately, one at a time ("single-cell" or "single-character" design) (see also [9], [31]–[34]). Dimension reduction by PCA and Fisher Discriminant Analysis (FDA) classifier are applied to nonaveraged, single-trial data. For *MindGame*, the authors reported a 66% mean accuracy (specifically, this was the rate at which the correct target was selected out of 12 possible targets).

C. Bacteria Hunt

In the P300 variant of the *Bacteria Hunt* BCI game [35] stimuli are presented on images of "bacteria" not in rows and columns, but rather in unstructured groups. This feature allows the images to be freely positioned on the screen. The following stimuli can be used: the changing of the color of an image of bacteria from orange to black or the enlargement or rotation of an image.

D. Brain Invaders

In *Brain Invaders* [36], the user must destroy an "alien" by concentrating on it. The aliens can be placed on a grid or arbitrarily positioned on the screen. The grid with aliens moves on the screen following the original *Space Invaders* design. As in *Bacteria Hunt*, the stimuli in this game can be presented in spatially unstructured groups. A combination of a color change and item enlargement is used as the target stimulus, whereas for the nontarget items, only an increase in the brightness is employed. The targets are assigned by the computer. If an alien selected on a single-trial basis is the target, that alien is removed from the display. Otherwise, the stimulation continues, and the next selection is made on a two-trial basis, and so on, until either the target alien or 14 nontarget aliens are destroyed. Linear discriminant analysis (LDA) preceded by spatial filtering with the xDAWN algorithm [37] is used for the classifier training. The calibration procedure lasts for only three minutes.

E. Mind the Sheep!

In *Mind the Sheep!* [23], the user starts and stops stimulation using the mouse button, thus controlling the trade-off between the stimulation duration and the selection accuracy. After the stimulation stops, one of three dogs selected by the BCI as attended moves to the location indicated by the mouse. The sheep move randomly by default and move away when a dog approaches. The user's task is to direct the sheep to a pen. As in *MindGame*, stimuli are not grouped. An area measurement method is used to classify the EEG responses.

F. A face card game

In a BCI face card game described in [38] the P300 BCI matrix is populated with face cards. The cards are face-side down by default and are shown as face-side up when selected by the BCI. If these cards do not match, they return to the face-side down position. The authors of this study emphasized that the effectiveness of the P300 BCI classifier is affected by the user's motivation during the calibration, and proposed to intentionally use games to enhance motivation.

G. Using the P300 BCI to stop during virtual driving

The use of a P300 BCI in [39] is similar to gameplay and, following Plass-Oude Bos *et al.* [19], we include this paper into the review. A go-cart is used for non-BCI control of a virtual car, and the task is to stop at red traffic stop lights while driving in a virtual reality. Stopping is triggered by a single-trial recognition of the P300 wave. In a pilot study, mean accuracy of the classifier was 83% using a robust Kalman filter.

H. MindPuzzle[1]

MindPuzzle was proposed in [40] and implemented by the authors of this paper with the participation of S. V. Logachev. In this BCI game, the user assembles a puzzle (Fig. 2, right panel on the screen) from its fragments (Fig. 2, middle panel). Highlighting the rows and columns of the matrix with the fragments is used as the stimuli.

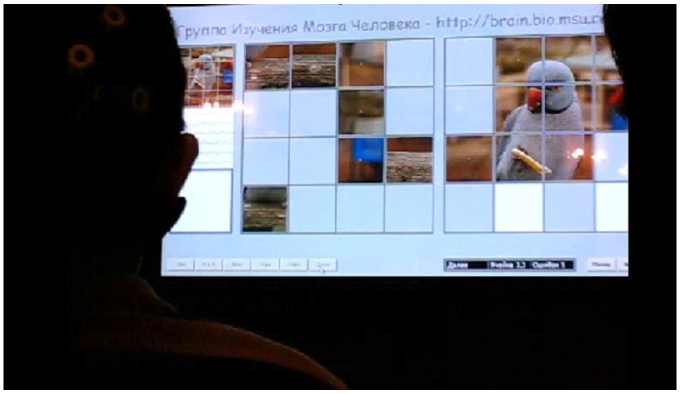

Fig. 2. *MindPuzzle* being assembled in a public demonstration (IV Moscow Science Festival, 2009).

In contrast to a typical puzzle game, the user only needs to select a fragment but not to indicate where the fragment goes. This piece is automatically moving to the correct position in the right panel, but only on the condition that the fragment belongs in one of the two positions randomly specified by the program at the beginning of the turn and indicated in white (Fig. 2, right panel). If a fragment that should be in another position is selected, that piece is not moved, and an error is counted. An exception is made for the first three attempts in the game; any fragment chosen in these attempts is moved to

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[1] This game has been described so far without including certain important details due to the format of the publications (i.e., a patent). To provide access to these details, we describe it here more extensively than the other games.

the correct place. This exception helps the user to become confident that he or she is indeed controlling the game with his or her mind.

Unlike in the standard P300 BCI, the stimulation matrix of *MindPuzzle* and the groups of stimuli change during the game. More specifically, the cells from which the fragments are taken are left empty and are not highlighted during later turns (Fig. 2). Stimulation is started with mouse click. The calibration phase, in which 100 target and 300 nontarget EEG epochs are collected, lasts two minutes. LDA is used as a classifier.

MindPuzzle's satisfactory performance was repeatedly confirmed in a number of demonstrations under "field" conditions, with the participation of BCI-naпve users. These users included television journalists playing *MindPuzzle* in front of the camera and public-events visitors. In particular, at the IV Moscow Science Festival (2009, Lomonosov Moscow State University) *MindPuzzle* 34 of 37 visitors successfully assembled a full puzzle within the time limit of 20-25 min in a noisy and distracting environment.

I. Billiard Puzzle

Similarly to *MindPuzzle*, in *Billiard Puzzle* [41], [42], the goal of the game is to assemble a full image from its fragments. The stimuli consist of the highlighting of these fragments. For each turn, the user begins the stimulation via a mouse click. There is, however, a unique feature that is not found in any other P300 BCI: the items on which the stimuli are presented move continuously, at a speed of approximately 5°/s. The stimuli are independent of the movement and are presented without grouping. The fragments are labeled with letters and should be selected in alphabetical order (Fig. 3). FDA is used as a classifier.

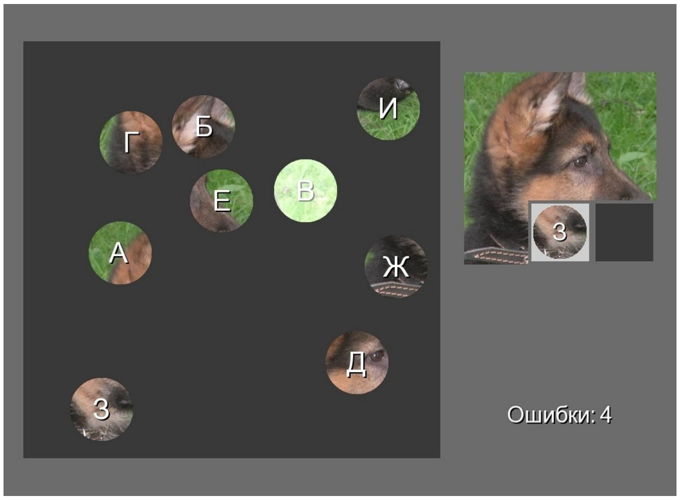

Fig. 3. *Billiard Puzzle* display. Each ”bouncing ball“ contains a fragment of the image being assembled on the right. The order of the targets is cued by letters of Russian alphabet, and the current target is indicated by a circle in the right panel. The ball labeled with the letter ”B“ is flashing. At the bottom right, a counter shows the number of errors (here, 4 errors).

In a four-session study this P300 BCI game was played by two groups of participants, one in single-trial mode and another in triple-trial mode. The accuracy was 65% in the single-trial group and 81% in the triple-trial group. No dependence on the session was found [42].

J. Overcoming the shortcomings

The above review of the existing games shows that the deviations from the standard P300 BCI design help to overcome or alleviate the problems related to this BCI as listed in the Introduction:

"(1) Separated stimuli and action" — This problem is solved in *Bacteria Hunt*, *Brain Invaders, Mind the Sheep!,* the cited face-card game and *MindPuzzle,* in which the action affects the same objects on which the stimuli are superimposed. In *MindGame*, the locations of the stimuli are the points to which the controlled character is moving, allowing attention to be naturally directed to these locations. In *virtual driving*, the stimuli are traffic lights whose spatial remoteness from the vehicle is realistic and also likely do not lead to the division of attention.

"(2) Simple, static and stereotyped stimuli" — In the majority of games the visual design is enriched by various changes occurring during the game, and/or by the free positioning of the stimuli in space. In *Brain Invaders,* the destroyed aliens are removed from the matrix, whereas the dogs and sheep change their positions in *Mind the Sheep!*. In *MindPuzzle*, the correctly selected puzzle fragments are removed from the matrix, and these fragments' positions are no longer highlighted. At the end of this game, only one cell is flashing. Both in *MindPuzzle* and in *Billiard Puzzle* the items highlighted during stimulation are unique pieces of the image to be assembled, so they typically possess colored and highly variable content. In *Mind the Sheep!*, the visual display is enriched by the movement of the sheep, whereas in *Brain Invaders*, the stimulation matrix moves, and in *Billiard Puzzle*, target and nontarget "balls" move on different trajectories.

"(3) Goal selection instead of process control" — The majority of the reviewed P300 BCI games are turn-based games, in which discrete selections are natural. Partly continuous control is implemented in *MindGame* in the form of gradual feedback frequently provided on a single-trial basis. In *Mind the Sheep!*, gradual control in the form of cursor positioning is executed using a non-BCI tool (a mouse). In *virtual driving*, the BCI is used only for stopping at red traffic lights, whereas usual, non-BCI methods are used for continuous control.

"(4) Repeated stereotyped mental actions required to trigger a single action in the game" — Although single-trial operation is not often reported in the P300 BCI literature, this approach is already used in five of the eight reviewed designs. In *virtual driving, MindGame* and one of the modes of *Billiard Puzzle*, actions are always performed on a single-trial basis. In *Brain Invaders and Mind the Sheep!* the length of stimulation varies, and a single-trial mode is possible.

"(5) The need to use mental actions unnaturally mapped to virtual-world actions" — This problem was solved in *virtual driving*: the action of stopping the vehicle well fits the user's

preceding mental note of the red light.

"(6) The P300 BCI as a "synchronous" BCI" — The need to synchronize each BCI-mediated action to the external stimuli is the most serious problem in applying the P300 BCI to games. In the single-trial mode, time moments to which the user should synchronize the action are frequently available, thus the problem is partially alleviated. A more radical solution is the use of the P300 BCI control for actions that are normally "synchronous", such as stopping when a traffic light switches to red, and a non-BCI control when gradual control is needed, i.e. the solution already discussed for the problem (3).

The reviewed P300 BCI-controlled games were only tested in healthy individuals. However, the majority of methods used to overcome the shortcomings of the P300 BCI may also be applicable to games for paralyzed users.

III. Relevant trends in current P300 BCI research and development

Many efforts have been made to improve the P300 BCI computational algorithms (see [6], [14], [43]–[45] for review). To increase the accuracy and/or speed of the classifier using a limited amount of data for training, linear and nonlinear Support Vector Machines (SVM) and Bayesian classifiers were applied as alternatives to LDA and related techniques, such as Stepwise Linear Discriminant Analysis (SWLDA). Regularization techniques were found to significantly increase LDA accuracy. With shrinkage regularization, LDA outperformed SWLDA, especially in single-trial classification [14]. "Asynchronous" P300 BCIs do not issue commands until the user starts attending the stimuli [46], [47].

In most publications, only the P300 wave is mentioned as a component used for classification in the P300 BCI. Nevertheless, ERP studies have emphasized the role of other components [31], [44], [48]–[53], especially the negative component N1 observed at occipital and parieto-occipital locations, with a peak at approximately 200 ms. This component, however, depends on gaze [51], [52] and therefore is not helpful for severely paralyzed patients with impaired gaze control. (It should be noted that the use of gaze control in operating the P300 BCI actually contradicts the definition of a BCI as a means of non-muscular control. However, the role of gaze in the BCI control is not obvious to the users. Moreover, the P300 BCI can be operated in a similar way using either overt or covert attention, i.e. with or without fixating the targets, although the accuracy is much higher in the former case [51]. In the P300 BCI literature, the term "BCI" is thus used even when it is evident that gaze-dependent ERP components significantly contribute to control.) Because most of the classifiers currently used in the P300 BCI utilize the data from all of the electrodes and from wide time intervals, these classifiers capture the N1 in addition to the P300. However, this is only true if relevant electrode locations are used, which is not always the case; note that very different positions, mainly Pz and Cz, are typically recommended for the P300. It is also important to consider the lack of this component's use in severely paralyzed patients when BCIs designed for these patients are tested in able-bodied people.

The classifier training time can be significantly reduced by enabling classifier adaptation after the initial training [54]–[56]. Unsupervised approaches to classifier training can utilize the data from other individuals [57] or exploit the constraints imposed by the BCI stimulation setup [58]. If calibration is used, it can be 'hidden' in instructions provided before starting the game, in a simplified version of the game or in a startup phase of the game when traditional (mechanical) input devices are used [15], [19]. A simplified protocol with only target stimuli may reduce the risk of calibration failures due to a misunderstanding of the instructions [59].

In addition to highlighting, a large variety of visual events work as stimuli in the P300 BCI: darkening of the characters [53], [60], change of color [61], [62], placing contrast lines over the pictures [63], increase in size [63], [64], shift of the stimulus position [62], rotation of a background figure or the content of the picture [63], [65], contraction of a circle [66] or movement of a bar [66]–[69] near the attended target, or flashing of famous faces [70], emotional faces [71] and inverted faces [72]. The P300 BCI classification accuracy was not affected by the movement of the stimulation matrix at speeds of 5°/s and 10°/s [73].

Accuracy may be increased by adding audio or tactile modalities to the visual P300 BCI design (especially in patients with poor vision) [74], [75] or by the hybridization of different BCIs with each other or with input devices based on other signal modalities (e.g., eye trackers) [4], [76], [77].

The general issues important in the development of consumer BCI devices and software, such as reducing the cost of the hardware, replacing wet electrodes with "dry" electrodes, ensuring the stability of performance under conditions highly different from laboratory experiments, and automatically handling artifacts (see [3], [4], [8], [78] for review), are critical to the BCI games as well. The P300 BCI uses relatively slow and high-amplitude components of the EEG signal, so the required characteristics of the amplifiers and the electrodes can be relatively relaxed. However, this may not hold true if the BCI makes decisions on a single-trial basis, a mode requiring a signal-to-noise ratio to be as high as possible.

Recently, it was demonstrated that a technology similar to that used in the P300 BCI can be used in "BCI attacks" aimed at capturing private information from the users [79]. These concerns may need to be addressed in the development of commercial or publicly available P300 BCI games.

IV. The nearest future of the P300 BCI games

The very simple P300 BCI games that have been proposed already demonstrate the flexibility of the P300 BCI technology. Compared with the "classical" P300 BCI design, the reviewed BCI games have new elements and features (listed in Section II J) that can be used in future work on P300 BCI game development. New solutions from the more general

P300 BCI research (listed in Section III) can be used to further enhance the technical characteristics of the interface, its usability and its ability to be flexibly adapted for use in games.

Paralyzed patients may benefit from small changes in the interface that make it possible to use the P300 BCI to control existing turn-based games, such as chess or *Second Life* (Section II). Due to the ability of the P300 BCI to select from many commands in one step, this BCI is well-suited to such games. It is less likely that a severely paralyzed patient could use a fast BCI control, such as the single-trial P300 BCI mode. Healthy users, who can play games using the usual input devices, may be primarily interested in the BCI control for its ability to provide an intensive unusual experience, and thus may need to be more dynamic and integrated into the game design. The games that we reviewed show possible directions for such integration.

The most important idea, in our view, was proposed by Bayliss and Ballard in the *virtual driving* design [39]. This idea is to use, as a single target stimulus, a natural discrete event that may occur at an attended location. In [39], the event is traffic light turning to red. The same idea can be used, for example, in games where the task is to kill enemies in a virtual world: certain movements or transformations of the enemy avatar can be used as the target stimuli. With single-trial mode, the shortest possible BCI response can be ensured.

Significant designer work and HCI studies are still required to render the P300 BCI games engaging and exciting even after the first use. However, the simple P300 BCI games, such as reviewed in this paper, can be useful for introducing individuals to the BCI technology, as no training is required to start playing. The P300 BCI games may be included in software distributed with a consumer BCI gaming device, ensuring that most people who purchase the device are able to experience the BCI control without prolonged training.

Another use for simple P300 BCI games is, in our opinion, in studies of possible attention training effects, which may utilize the P300 wave's strong dependence on attention. In particular, single-trial operation and gradual feedback dependent on the BCI classifier output, as in *MindGame* [13], can be used in such studies. As suggested by preliminary results obtained in our four-session study with *Billiard Puzzle* [41], [42], even the interest generated by a simple P300 BCI game may be sufficient to ensure participation in multiple sessions with engagement in the play.

ACKNOWLEDGMENT

The authors would like to thank the editors and the reviewers for constructive comments that significantly improved the paper.

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