BRAIN-COMPUTER INTERFACES AND AUGMENTED REALITY: A STATE OF THE ART

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ABSTRACT: This paper reviews the state of the art of using Brain-Computer Interfaces (BCIs) in combination with Augmented Reality (AR). First it introduces the field of AR and its main concepts. Second, it describes the various systems designed so far combining AR and BCI categorized by their application field: medicine, robotics, home automation and brain activity visualization. Finally, it summarizes and discusses the results of the survey, showing that most of the previous works made use of P300 or SSVEP paradigms with EEG in Video See-Through systems, and that robotics is a main field of application with the highest number of existing systems.

INTRODUCTION

Research in the field of BCIs has gained more and more popularity over the past few decades. BCIs have been used in a wide variety of applications, rehabilitation [3], robotics [7], entertainment [24] or in association with different input modalities: gaze trackers or electromyography systems. They have also extensively been used in Virtual Reality contexts [27], and more recently with Augmented Reality [22, 30], which is itself gaining more interest nowadays.

Brain-Computer Interfaces and Augmented Reality are two fields that can be combined for interaction and/or visualization purpose. On the one hand, AR-based systems usually rely on Head Mounted Displays (HMD) equipped with cameras, that can be used in scenarios requiring hands-free interaction [9]. BCI paradigms can provide such means of input, either to interact with virtual [16] or real objects [36]. On the other hand, BCIs can take advantage of AR in order to interact with the real world. AR can also provide interesting ways of displaying feedback by integrating it in the real world environment. This feedback is important for a BCI-based system to enable users to access and modulate their cerebral activity [26, 32].

Despite this, combining BCIs and AR is not an easy task. Many constraints have to be taken into consideration. First, at the hardware level, both technologies can require head mounted devices that cannot easily be worn at the same time and, if worn, it is necessary to make sure that they do not interfere. BCIs use very low amplitude signals and are thus very noise-sensitive. Then, software constraints have also to be taken into account. It is for instance necessary to have a middleware or an intermediary agent in order to synchronize between them and to combine inputs. Finally, recording brain activity in the context of AR where users are generally free to move may also be difficult as muscle activity provokes artifacts in the BCI recordings [17].

This paper aims to give an overview of the state of the art of systems combining BCIs and AR. Section **2** introduces the field of augmented reality, highlighting some of its most important concepts. Section **3** reviews existing BCI-AR applications, by categorizing them according to their application field. Section **4** summarizes and discusses the results of our survey. Finally, section **5** is a general conclusion.

INTRODUCTION TO AUGMENTED REALITY

Definition of Augmented Reality

Augmented Reality relates to the integration of virtual objects and information in the real world in real-time [40]. According to Azuma [5] three characteristics define an AR system: (1) the combination of real and virtual content, (2) the real-time interaction, (3) the 3D registration of the virtual content in the real environment. Contrarily to Virtual Reality where the user is immersed in a completely virtual world, AR mixes virtual and real content, ideally, making them appear to coexist in the same space [5].

Milgram and Kishino [31] established a continuum ranging from complete virtuality to complete reality. Between them, exist different combinations of real and virtual environments, depending on the level of each one in the scene (see Figure 1).

In the scope of this paper, only visual AR applications are considered.

Types of Augmented Reality

Augmented Reality is generally divided between: (1) Video See-Through (VST) AR: in which real images are

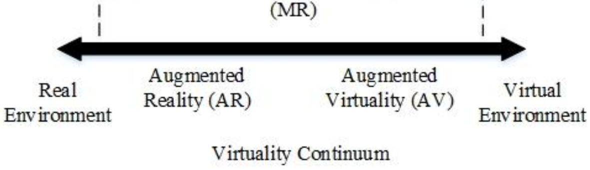

Figure 1: Representation of Milgram and Kishino Virtuality continuum of mixing real and virtual environments (from [31]).

shot by the camera of a device (tablet, phone, etc.) before being visualized through a screen, augmented with virtual information; (2) Optical See-Through (OST) AR: in which the virtual content is directly displayed in front of the user’s eyes onto a semi-transparent screen (e.g., Microsoft Hololens); and (3) Projective AR (a.k.a. Spatially Augmented Reality): in which virtual content is projected into a real environment object [4].

Tracking and Registration

An essential part of any AR system, is the ability to collocate virtual and real objects, which is known as registration. Afterward, tracking allows to properly render the change in virtual objects according to the position of the camera and thus, ensuring their credible integration into the real world [40]. Registration of virtual elements can be done using fiducial markers placed in the real environment, through pattern recognition techniques to identify real objects or with active sensors [5]. One popular way of achieving the tracking, consists in using the Simultaneous Localization And Mapping (SLAM) algorithms [8] related to the resolution of the problem of enabling a robot to simultaneously discover its surroundings and infer its position [37]. Originally designed for robots’ navigation [14], it has been adapted for use in AR [13] as it allows the tracking of objects in unknown environments [8].

Interaction

Interaction is a major challenge for AR as it is necessary to provide the user with means to act on the virtual elements [40] and to manipulate them. However, being in the context of wearable computers, new ways of interaction, different from mouse and keyboard, have to be employed. So far, this has mainly been done through voice commands and hand gesture recognition [21] (as with Microsoft’s Hololens), gaze tracking [20] or with physical buttons [34] (as with Google Glasses). BCIs could particularly contribute to AR-based systems interaction means, especially on visual selection tasks that can be done via SSVEP or P300 for example [19, 25].

APPLICATIONS COMBINING AR AND BCIs

In theory, combining AR and BCI could potentially be applied to most topics where BCIs can, e.g. assisting disabled people, entertainment, sports. There are different reasons why to combine AR and BCI. First, from a BCI point of view, AR offers new ways to integrate feedback in real world environment, thus, bringing new interaction possibilities and enhancing the user experience. Second, from an AR point of view, BCIs offer new hands-free paradig(te)-13( )-327()-110(P)-9(3)6(0)327(qin)7(te)-3g0 G[(()5(ilit)4(ies)-48(an)4(d)-5( )] TJETQ0.0000088

Figure 2: examples of applications combining AR and BCIs (a) Surgeon laser microsurgery training [6]; (b) Home automation system to control a lamp using P300 [36]; (c) TEEGI, brain activity visualization puppet [18] (d) MindMirror: brain activity visualization [30].

environment to allow disabled people to safely learn how to drive a wheelchair. Among different modalities to drive the wheelchair, they designed an SSVEP-based solution to control the direction. The goal of AR in this system was to be able to provide different driving scenarios by integrating virtual obstacles to the real world scene while still ensuring users' safety.

Robotics

BCIs and AR have particularly been used in the field of Robotics: (1) to explicitly steer or control a robot agent or (2) to manipulate a robotic arm. It is possible through AR, to provide a first-person view of the real world, augmented with contextual visual commands. This has been demonstrated by works like Escolano et al. who developed a P300-based AR system to control a mobile robot [15]. The robot was in a different room, equipped with a camera displaying a first-person view on a computer screen, augmented with a P300 menu to control it. A similar work had also been done by Gergondet et al. [19] who proposed a system to steer a robot using SSVEP. Their system allowed users to control a robot equipped with a camera displaying the augmented robot's view on a computer screen. But in this case, the menu consisted on four flickering commands. In addition to merely steer the robot, it was possible to select different speeds. Petit et al. developed a robot navigation system to allow users to interact with a robot [33]. Thanks to a fiducial marker placed on the user's VST HMD, the user can make the robot come towards him. Then, a body part selection happens with fiducial markers placed on different parts of the user's body beginning to flicker so that they can be selected through SSVEP for the robot to interact with.

BCIs and AR have also been used to control robotic arms through goal selection (shared control) rather than step-by-step control. This has notably been done by Lenhardt and Ritter [25] who have used a P300 oddball paradigm in order to make a robotic arm move real objects on a table. The objects were 5 cubes tagged with AR markers that had 3D virtual numbers appearing on top of them when seen through a VST HMD. The numbers were highlighted in a random order to elicit a P300 response when the user wanted to select one of them. When an object was selected, a grid appeared on the table. Each case representing a possible target destination that was also selected through the P300 paradigm. After the selection of both target object and destination, the robotic arm performed the motion. Another robotic arm control project has been achieved by Martens et al. They designed a robotic arm for two tasks [29]. The first consisted to select and move objects through P300 paradigm. The 'stones' to move were augmented when seen through a VST HMD so that the user could focus on the stimuli. The second task was to control the robotic arm to insert a key in a keyhole and was done through the augmentation of the HMD view with four SSVEP commands. Lampe et al. have used Motor Imagery (MI) for the purpose of controlling a robotic device present in a different location than the user [23]. The robot was equipped with two cameras, one for hand view and the other for the scene view, and both displayed on a computer screen. Whenever a selectable object entered the field of view, it was augmented so that the user could select the object to grasp through MI, and the robotic arm autonomously grabbed it. In this case, three commands were sent through Motor Imagery: *left*, *right*, to select which object to grasp, and *confirmation*. These commands respectively corresponding to left or right finger tapping and toe clenching.

Home automation

Another application is the ability to control smart environments, whether it is to provide comfort automated mechanisms or assistive control to manipulate home appliances. In this case, combining BCIs and AR is achieved through mainly two different strategies: (1) direct interaction [36], (2) indirect interaction through a robot agent [22].

The first strategy has been used by Takano et al. in a P300-based AR-BCI system to control multiple devices at home [36]. They tagged house appliances with AR markers which, when seen-through an Optical See-Through (OST HMD), make a control panel appear over them. The P300 paradigm is then used to select the command to execute (see Figure 2 (b)).

Indirect interaction has been proposed by Kansaku et al. [22], with a system that allows users to control a distant robot in a house environment through brain activity. The robot was equipped with a camera displaying a video stream of its environment where appliances were tagged with fiducial markers. When one of them entered the robot's field of view, a control panel was displayed, allowing users to control it.

Brain activity visualization

BCIs can also be useful for brain activity visualization purpose. Whether it is (1) for neurofeedback or (2) for pedagogic reasons, AR can offer a natural way to display how the brain works and integrate it in real life context.

The notion of neurofeedback is an essential part of the training for BCI use [28]. Neurofeedback has been provided in AR either by projecting it on real life objects [18], or displaying it directly on the representation of the user [30]. Mercier-Ganady et al. [30] developed an application called MindMirror using AR for the purpose of neurofeedback. The system consisted of a smart mirror - a LCD Screen with a facing camera - displaying the user in a somehow X-Ray vision way (see Figure 2 (d)) showing him/her the activated areas of his/her brain through EEG measurement. More precisely, the system displayed the distribution of the electrical potential over the surface of the virtual brain. Frey et al. developed a projected AR system called Teegi [18]. It consists on a tangible figurine on the head of which, the recorded EEG of the user is displayed (see Figure 2 (c)). The goal of Teegi was educational as it was designed for people to understand how EEG works.

Research studies

Some works do not totally fall in one of these categories. They are proof of concepts and feasibility/research studies. It is the case for the system of Faller et al. who developed a proof of concept of SSVEP-based BCI to control a virtual character augmented on a real table [16]. Their system included a VST HMD device, and the users' goal was to make the character move through a series of points represented by flickering checkerboards. Another feasibility study was performed by Uno et al. who wanted to determine the effect of an uncontrolled real space background on the performance of a P300-based BCI [39]. Their preliminary results showed no effect of real space background on the selection accuracy, thus encouraging the use of combined AR-BCI applications. Chin et al. developed a prototype in which users could reach and grasp virtual objects augmented on a real table [11]. The user’s hands were augmented with virtual ones that he could control through Motor Imagery. The whole scene was displayed on a computer screen and no impact of AR was found on MI performance. Another type of applications has made use of fNIRS in the context of wearable devices. Afergan et al. developed a fNIRS-based BCI called Phylter [2]. Used in combination with Google Glasses, their system helped prevent the user from getting flooded by notifications. It was passively analyzing user's cognitive state to determine whether or not he/she could receive notification. The decision was based on the level of cognitive workload of the user determined after training the classifier on different user’s states. Still using fNIRS-based BCIs, Shibata et al. presented a prototype of a Google Glass application called Zero Shutter Camera [35] which consisted on a passive photo trigger, based on user's mental workload. The system took the predicted user mental state as input and automatically triggered a camera snapshot at 'special moments' estimated when user's mental workload was above a threshold determined through training**.**

DISCUSSION

Table 1 summarizes the previous works combining AR and BCIs according to the BCI paradigm, the type of AR display and the brain sensing technology used. This table shows first that most of the time augmentation is done either through computer screens or HMDs, and that only a few number used Optical See-Through AR. The reason

Table 1: Overview of previous systems combining AR and BCIs. **CS**: Computer Screen; **VST**: Video See-Through; **HMD**: Head Mounted Display; **OST**: Optical See-Through; **HA**: Home Automation; **PoC**: Proof of Concept; **M**: Medicine; **BAV**: Brain Activity Visualization; **SAR**: Spatially Augmented Reality. **N.A**: Proof of concept, no AR implemented. **M.W:** Mental Workload.

Work	*BCI paradigm*	*AR type*	*AR display*	*BCI sensor*	*Field*	*Objective*
Escolano et al. [15]	P300	VST	CS	EEG	Robotics	Robot steering
Lenhardt et al.[25]	P300	VST	HMD	EEG	Robotics	Robotic arm control
Takano et al. [36]	P300	OST	HMD	EEG	HA	Direct HA
Kansaku et al. [22]	P300	VST	CS	EEG	HA	Indirect HA
Uno et al. [39]	P300	VST	CS	EEG	PoC	Feasibility study
Martens et al. [29]	P300/SSVEP	VST	HMD	EEG	Robotics	Robotic arm control
Broges et al. [10]	SSVEP	N.A	N.A	EEG	M	Wheelchair control
Gergondet et al. [19]	SSVEP	VST	CS	EEG	Robotics	Robot steering
Petit et al. [33]	SSVEP	VST	HMD	EEG	Robotics	Robot steering
Faller et al. [16]	SSVEP	VST	HMD	EEG	PoC	Virtual char. control
Lampe et al. [23]	MI	VST	CS	EEG	Robotics	Robotic arm control
Chin et al. [11]	MI	VST	CS	EEG	PoC	Virtual hand grasping
Correa et al. [12]	MI/EMG	VST	CS	EEG	M	Phantom Pain therapy
Blum et al. [9]	EMG	VST	HMD	EEG	M	Surgeons assistance
Barresi et al. [6]	Concentration	VST	HMD	EEG	M	Surgeons training
Acar et al. [1]	Raw data	VST	Smartphone	EEG	M	Phobia therapy
Mercier et al. [30]	Raw data	VST	CS	EEG	BAV	Neurofeedback
Frey et al. [18]	Raw data	SAR	Puppet	EEG	BAV	Education
Afergan et al. [2]	MW	OST	HMD	fNIRS	PoC	Proof of Concept
Shibata et al. [35]	MW	OST	HMD	fNIRS	PoC	Proof of Concept

for this may be that the first solution is convenient for prototyping and the second very intuitive, enabling more mobility for users. However, if screen-based AR clearly prevents users from moving, the state of BCIs development so far, also prevents them from moving with HMDs due to the risk of muscle artifacts. As combining AR and BCI is relatively new, the question of mobility did not seem to be discussed in most of the papers using HMDs. But, the development and improvement of BCI technology, notably developing filtering methods to efficiently remove muscle artifact is a prerequisite for using BCIs as AR interaction tool to its full potential. The second observation that can be made is that the majority of works has made use of EEG. A reason may be the real-time nature of AR interaction, for which the time resolution of EEG seems more appropriate than fNIRS for example. Regarding BCI paradigms, although a number have been considered, SSVEP and P300 paradigms are the most used ones. This popularity could be due to the graphical aspect of the augmentation, as AR is based on displaying graphical virtual elements on the users' field of view, hence, vision-based paradigms are well suited for selection tasks. However, it is important to explore more deeply the effect of AR on BCI performances, not only from the system point of view but also in terms of users' cognitive load as evolving in a AR context may be more cognitively demanding. In addition, most of the works were still at the stage of prototypes. They made use of intermediary computers to translate brain activity and integrate it in the interaction. If SSVEP seems rather robust to synchronization issues, P300 is probably more sensitive to jitter. Using intermediary computer between BCI and AR device might introduce a bias and decrease P300 performances. A solution to this, could be to develop all-in-one wearable devices, powerful enough to directly process mental activity, this would dispense from the use of external intermediary agent and reduce the risk of desynchronization. Besides, it could be interesting to explore other BCI paradigms in AR context. Covert Attention [38] for instance could be interesting to study as AR implies elements in the whole field of view of users with no limitation to the screen's borders. It is noticeable from Table 1 that most of the works relied on active BCI paradigms (including reactive). They were mostly used for manipulation and voluntary control of physical or virtual objects. Passive BCIs have for their part, mostly been used for gathering neurophysiological information about the user to determine his mental state. Such passive paradigms could be more deeply studied in future works.

Finally, it seems necessary to consider AR-BCI systems from a Human-Computer Interaction perspective to evaluate and improve them. In addition, more and other fields of application could study and benefit from combining AR and BCIs in the future. Examples include: entertainment and gaming, rehabilitation, education, or communication and videoconferences.

CONCLUSION

This paper presented the state of the art of combining Brain-Computer Interaction an Augmented Reality. It first introduced the field of AR which can be divided into Optical See-Through, Video See-Through and Projected AR. Then it presented the previous works combining AR and BCIs in the fields of medicine, robotics, home-automation, brain activity visualization as well as proofs of concept or feasibility studies. Our survey showed that most of the previous works made use of P300 or SSVEP paradigms in VST setups, that EEG was the most employed brain sensing technology and that robotics was the field with the highest number of applications. Combining AR and BCIs seems useful in scenarios favoring hands-free interaction, but there is little doubt that future works will explore this combination in many more application fields, and that new interaction techniques will be designed as well as new feedback modalities will be invented, taking advantage from both technologies.

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