BCI seminar
Towards BCI-Based Interfaces for Augmented Reality, Review Of A Paper
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***Abstract*—This scientific report is aimed at reviewing the paper *Towards BCI-Based Interfaces for Augmented Reality: Feasibility, Design and Evaluation*, Si-Mohammed et al. [1]. Here, a literature review is accomplished to look at both the scientific context in which the paper was at the time of its publication, and what the paper brought to the scientific community after its publication by IEEE, analysing the scientific findings based on Si-Mohammed et al. work. Furthermore, the particular study is analysed, including its methods, results and the interpretation that the authors provided. This review has the main aim to communicate the scientific findings of the reviewed paper: from the tolerance quantity of feasibility on AR-BCI system to the proposal of the design space into which develop SSVEP-based BCI on AR.**

***Note*: From now on, the reviewed feasibility study will simply be referenced as *the study*, formatted in italics, always referencing to Si-Mohammed et al [1].**

***Index Terms*—Brain-Computer Interfaces, Augmented Reality**

I. Introduction

Scientific literature in the blend of Augmented Reality and Brain-Computer Interfaces has been evolving during past 15 years. At the time in which this report is being written, the market size of technologies merging physical world elements with computer-generated ones like Mixed Reality is growing, reaching an estimated [2] Compound Annual Growth Rate (CAGR) of over 40% and an industry value over $3.7 billion by 2025. Scientific research has been done in the past [3] and now it seems that we are living the historical period in which this technology is exploiting its market potential. Another field that is growing, but still more in scientific research stage yet, is Brain-Computer Interfaces [4]: in the last 40 years, it passed from being part of simple communication programs, to sophisticated applications controlled with Brain-Computer interactions, reaching various applications even not health-related such as robotics or smart home appliances. A promising example of Brain-Computer Interfaces application is the blend with the already cited Mixed Reality technologies [5]. This blend could be the opportunity to see a cross-absorption of the potential of the two technologies: so to both an enhancement of Brain-Computer Interfaces market appealing and an opportunity for Mixed Reality to be discussed again by science, eventually enhancing the level of scientific research in the field. For this reason, reviewing *the study* is scientifically relevant, to understand the role of it into the scientific ecosystem and so understand the value that this kind of blend could bring to future users. Before diving deep into the paper review, in this chapter there are introduced the techniques used in *the study*, namely Augmented Reality, which is one of the Mixed Reality techniques, and Brain-Computer Interface. Then an introduction to *the study* itself is provided.

A. Augmented Reality

Augmented Reality, often referred with its acronym AR, according to Furht [6], is defined as *the technology that integrates the information given by world in real-time with computer-generated information*. Augmented Reality usefulness is to be found not only on the enhancement of what surrounds the user but even any indirect view of the user, such as video-streams, enhancing even the user's perception and interaction with the real world. Into the Milgram's *Virtuality Continuum* [7] concept, AR is the technology that is more related to the real environment compared with Augmented Virtuality techniques such as the famous Virtual Reality into the Mixed Reality umbrella term as illustrated in *Figure 1*. The classification of the possible techniques of this kind of technology in literature is made according to the kind of

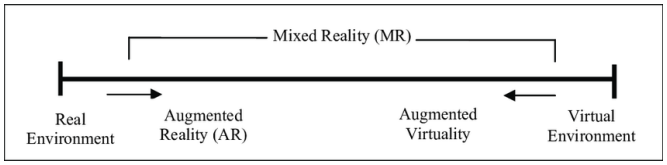


Fig. 1. Simplified representation of Virtuality Continuum

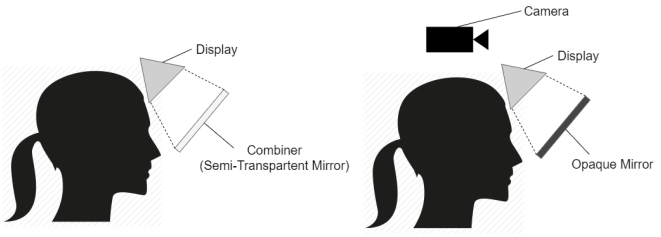


Fig. 2. Concepts of optical see-through (left) and video see-through (right) displays

display used: following Azuma [8] approach, it is possible to distinguish:

- *Head-Worn Displays (HWD)*: displays are mounted on the head of the user. As shown in *Figure 2*, there are two different types of HWD. One is optical see-through (OST) which provides an AR overlay through a transparent display, so that the physical world is directly visible through the lens. The other is video see-through (VST) where a video capture from a head-worn camera is used as a representation of the physical surrounding word and projected to an opaque mirror eventually enhanced with CGI. In the latter case, the physical world is only visible as a representation given by the camera.
- *Handheld displays*: flat-panel LCD displays used to provide VST based augmentations (e.g. smartphone, tablet, ...)
- *Projection displays*: the desired CGI is directly projected on the physical objects to be augmented.

B. Brain-Computer Interface

According to Wolpaw [9], *A brain–computer interface is a communication system that does not depend on the brain's normal output pathways of peripheral nerves and muscles*. Many applications are possible in this field. From a traditional medical approach, for example empowering patients that have problems at their muscles to interact with the surrounding environment [10], to other non-medical fields such as robotics or smart home appliances [4]. In *the study*, just a certain kind of paradigm is used to get the user input: Steady-State Visual Evoked Potential. According to Morgan [11], general Visual Evoked Potential (VEP) are non-invasive recordings of brain visual attention by means of amplitudes over time, measured in volt: those are able to describe some brain mechanisms and reveal spatio-temporal patterns of neural activities. Since VEPs are taken optimally at relatively long intervals (about 0.3-1.5 seconds), it is difficult to maintain a fair dose of attention for that period. For this reason, VEPs are particularly prone to noise: it is hard to distinguish between relevant and irrelevant stimuli. The alternative approach is the one of Steady-State Visual Evoked Potential(SSVEP): those are recorded as response to visual stimulus repeated at a steady rate by means of frequency, often 8-10Hz but even more. To use BCI, there are many software available. The one chosen in *the study* is OpenViBE [12], an open-source software platform to design, test and use BCIs for its particular easiness on the integration with high-end MR applications.

C. The study

As the name of the paper suggests, *the study* has 3 main goals. Each goal is tested over different independent user studies, each with a different setup and methodology base. (1) First goal is a feasibility study between AR technology and BCI. Indeed, BCI is an interface particularly prone to noise, and this problem could be a reason of failure of the AR-BCI blend. This section of the study addresses external noise given by external machinery, in this case the Microsoft's OST-HMD HoloLens. On the other hand, internal noise is addressed: that kind of noise generally not due to external hardware but rather on brain activity not directly related to the experiment. In *the study*, only movement of the head was addressed, since it is a common physical movement during a HMD usage and due to the fact that the neck is closer to the occipital lobe, that could bring potentially disruptive noise with itself. Each kind of noise is tested with a different user study. (2) The second goal of the paper is to propose a framework to design a user interface while combining AR and BCI. This is done basing on 5 dimensions: orientation, frame-of-reference, anchorage, size and explicitness. Even in this case, two different user studies are performed: one to determine the easiest perceived commands to control a robot with AR glasses and BCI, the second to evaluate the best frameworks derived on the previously done study basing on BCI performances. (3) The third and last goal, is to illustrate the development of a running prototype blending AR and BCI, basing on the findings of the previous sections. The prototype aims at controlling a physical robot with a predefined set of commands (go forward, turn right, turn left) prompted on the glasses' displays while using SSVEP as user input. In this case, just informal tests are performed.

II. Related Work

Throughout this section, the related work to *the study* is discussed. The section is divided into two sub-sections: the scientific context, addressing the literature background in which *the study* dived in at the time of the publication, and the development that *the study* brought to the scientific literature, addressing the contemporary scientific papers that used the findings of it. It is predictable from the nature of *the study* that the work previously done in literature combining Augmented Reality technology with Brain-Computer Interfaces is relatively small compared to the development that it brought to the scientific community, since it is a feasibility study and addresses the compatibility between a technology (AR) and an interface (BCI), involving a design layer.

A. Context

As it was predictable, the literature concerning the blend of AR and BCI at the time of *the study* was restrained. One early study coming from 2010 [13] suggests a division of the tasks between pick-up and placements in a BCI-controlled robot

through a grid displayed in an OST-HMD device. The tasks were asynchronous, meaning that the user had the control on when to perform the tasks. The same research group of *the study*, proposed a state of the art review [14] to the whole literature at that time addressing the blend of AR and BCI. The findings of this study were crucial for some decisions taken as motivation of *the study*: indeed, main findings are about the kind of applications, mostly robotics, and the BCI paradigm, mostly SSVEP. One approach reviewed by the group was the one from [15] which is yet another feasibility study which concentrates not only on AR but even in VR. According to this study, BCI has the power to enhance the stimuli that can be attached to physical world assets through AR and VR. Other studies where not only concerned solely on the feasibility of AR-BCI blend, but even with the BCI performance comparison with normal monitors. According to [16] performances of an AR-BCI system leveraging HMD are not different compared with LCD monitors: with a preference in occipital and mid-line channels: namely Fz, Cz and Pz for the latter and PO7, PO8 and Oz for the first. Finally, some smart home scenario was already present such as in the case of [17] in which the experiment was based in a BCI leveraging SSVEP and a HMD to control an elevator, some lights, and a coffee machine.

B. Development

At the time of this review, 57 published scientific papers are citing *the study*. Therefore, the examples that prove the importance of *the study* in the scientific community are numerous. In these papers, *the study* serves as background knowledge often in the introduction or in the related work sections, referencing to it as a study the proves the feasibility of the blend between AR and BCI. The application fields in these cases are different to a great extent. In the example from [18] a study is based on a proposed device for Industry 4.0 to inspect visually complex industrial plants by staring at them with a OST-HMD: *the study* here is used as feasibility study of reference for AR-BCI blend. In a smart-home study [19] AR and BCI are used to control 2 lights, a blind curtain and a music player from a television. Here *the study* has been crucial to choose SSVEP as a BCI paradigm given the high accuracy results obtained. A non-classical approach is the one from [20] that thanks to *the study* takes the AR-BCI fusion for granted and uses it as a neurofeedback tool for a meditation application. Another function that *the study* has on the citing papers is as benchmark for comparing accuracy with the accuracy measured by the papers. In this case, the citation often comes from the sections related to the discussion or conclusion. In [21] an online smart home control system is studied using AR and BCI. Here, the accuracy level proven by *the study* are beaten in the experiment. Another case is [22], in which the paper aims at finding the differences between a Personal Computer(PC)-SSVEP stimulus and an AR-SSVEP system concluding that for stimulus longer than 3 seconds there is not relevant difference, while for lower stimulus duration, time and layout of the stimuli have to be chosen carefully. Here, the accuracy is used to select the optimal threshold duration and as comparison for AR-SSVEP performances.

III. Methods

Since more than one research questions are risen during *the study*, in the course of this section and the next one, scientific methods and results are discussed separately for each research question. The research goals on the SSVEP-based BCI system are the following: (1) a feasibility study combining BCI and AR by studying the effects of internal and external noise on the performances, (2) propose a generic methodology to design a User Interface for SSVEP-based BCI using AR to display targets, (3) illustrate the development of a prototype of a BCI-based application in AR.

A. Feasibility Study

Throughout this part of the study, noise while blending BCI and AR is addressed. The interference brought by HMD on the BCI system, or external noise, is evaluated and compared with the performances of a LCD monitor-based BCI. Then, internal noise is addressed, meaning the kind of noise brought by the movement of the head to the SSVEP-based BCI system performance. Participant that took part in the experiments were always told about the nature of the experiment and signed a consent form at the beginning of it, accordingly to the Declaration of Helsinki.

1) Influence of AR Device on BCI Performance: in this user study, external noise is evaluated. Thirteen participants took part in the experiment. The participant, wearing a Microsoft HoloLens OST-HMD, had to sit at 2 meters from a LCD screen accordingly to the focal distance of the HMD. EEG data were recorded from a g.USBamp amplifier using a 10-20 system with visual cortex-related channels CPz, POz, O1, O2, Oz, Iz referenced to the ear and grounded to Cz.
Following the installation, participants performed 4 complete runs of SSVEP training, each of it during almost 7 minutes with 30 trials. During the runs, 3 white targets were displayed either on the LCD screen or on the OST-HMD. According to [23] and even previous literature [24] [25] generally SSVEPs have peaks at a frequency around 15 Hz, and the primary visual area on the visual cortex is elicited by visual stimulation at 5, 10, 15, 25 and 40 Hz. For these reasons, the three targets were chosen to be flickered each at the different frequencies 10, 12 and 15 Hz, being them visualized as circles with 10 cm long diameters arranged in the vertices of an equilateral triangle of 46 cm side. At first, participants were told to focus on a particular target by displaying a red arrow pointing at the target for 1 s. After 7 s, targets stopped flickering and a fake color feedback were displayed: there was no online classification, so one target was always colored by green for 2 s without having an actual feedback meaning, just for engagement. Indeed, correct targets were highlighted just 80 percent of the times, the incorrect ones were highlighted to keep participants motivated. The following trial started after 2 s break. In *Figure 3* the trial structure is visualized.
One run was composed by 30 trials, and 4 runs were com-

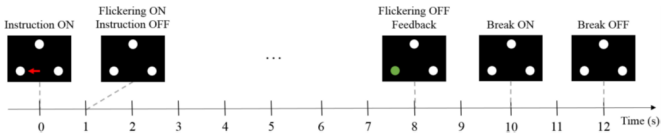


Fig. 3. Trial structure of the first user study with time reference visualized as x-axis. At t=0 the trial starts with three targets flickering at different frequencies: the user was told to concentrate on the target pointed by the red arrow. At t=1, the red arrow disappeared, the user continued to focus on that target. At t=8 a feedback was shown: 80 percent of the times the focusing target was highlighted, the remaining times another target was highlighted for engagement reasons. At t=10 the feedback stopped to be visible, while at t=12 the trial was finished and the system was ready to begin a new one.

pleted by each participant: each run with a different condition involving, or not, LCD display and/or the OST-HMD. The 4 conditions were: (C1) targets were displayed on the screen, HoloLens were not worn, (C2) targets were displayed on the screen while the HoloLens were worn but turned off, (C3) targets were displayed on the screen, HMD was on and turned on, (C4) targets were displayed on the HoloLens, while the LCD screen was turned off. The order of these conditions among the participants were randomized. Finally, classification accuracy was evaluated offline to estimate the impact of a OST-HMD on EEG data quality using SSVEP. The hypothesis was that the 4 conditions, C1, C2, C3 and C4, would not have relevant differences in classification accuracy.

This study, exposed a detailed offline analysis protocol for the measured EEG data. OpenViBE [12] was used sampling data at 512 Hz. Performances were evaluated using a 10-fold cross validation offline procedure by using 9 trials over 10 to train Common Spatial Pattern (CSP) to find spatial filters and Linear Discriminant Analysis (LDA) to discriminate attention on targets, and 1 trial was used to test. CSP filtered the data in sets of frequencies $\pm$ 0.25 Hz from their respective frequency:

- (9.75;10.25) Hz for the 10 Hz class
- (11.75;12.25) Hz for the 12 Hz class
- (14.75;15.25) Hz for the 15 Hz class

And then 6 optimal spatial filters were found, with maximum difference of EEG power one class to the others. Using a 500 ms time window and a 100 ms overlap, EEG signal power were spatially filtered. This result was used train an LDA to discriminate if the user was focusing on the target or not.

2) Influence of Users' Movements on BCI Performance in AR: in this user study, internal noise is quantified. Fifteen participants took part to the experiment. Participants wearing the Microsoft HoloLens OST-HMD were capable to see the visual stimuli as in the previous experiment (see *Figure 3*), using the same EEG tools. The participant had to stand up rather than sit in front of the LCD display: apart from this, the set-up was the same of the previous experiment.

Each participant was asked to perform 4 runs of SSVEP training each one composed by 36 trials as for *Figure 3*). On the HMD, 3 white moving targets flickering at the same dimensions and frequencies as the previous experiment (10 cm wide in a triangle of 46 cm side at 10, 12 and 15 Hz) were displayed. Time structure of trial and feedback strategy

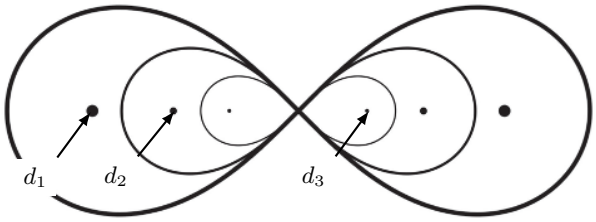


Fig. 4. Lemniscate of Bernoulli, used as head movement with half focal distances $d_3(40°) < d_2(100°) < d_1(160°)$.

was the same as the first experiment. What changed, were the conditions that this time were addressing the movement of the targets to focus on, reflecting directly in participants' head movement. The conditions were: (C1) no movement (static targets), (C2) a low-intensity movement configuration with a maximum amplitude from left to right of 40 degree, (C3) a medium-intensity movement configuration with a maximum amplitude of 100 degree and (C4) a high-intensity movement with a maximum amplitude of 160 degree. Conditions were in randomized order among 12 trials for each run. The movement of the head to be accomplished by the participant was the lemniscate of Bernoulli with different distances d_i as shown on *Figure 4*: participants were told to maintain the chest straight so that they could just move the head. The time in which the movement had to be performed was fixed at 7 s while the focal distance of the lemniscate d_i was changing. By doing so, smaller lemniscates were performed at lower speeds, and higher lemniscates at higher speeds.

B. A Design Space for BCI-Based User Interfaces in AR

In this segment of the study, the User Interface is addressed for the usability of the system. Accordingly to the experiments made on the feasibility section, 3 SSVEP targets were used, choosing the example of the control of a mobile robot as case study in which the three targets had three commands: (1) go forward, (2) turn right, (3) turn left. Here, the design space is first defined, then two experiments are shown. A first experiment is aimed at finding the most preferred paradigms in a qualitative way among a set of possible design choices illustrated beforehand, a second study points out the quantitative best ranked related to their performance on AR-BCI blend.

1) Design Space of SSVEP Target Display Strategies: the number of SSVEP targets to use were 3 as previously done by the feasibility study. The commands should move a Pioneer 3-DX robot, so the options were "Forward", "Turn Left" and "Turn Right". 5 dimensions were then defined to describe all the possible design layouts of the user interface as shown in *Figure 5*. Being 5 dimensions with 2 possible settings each, there are $2^5 = 32$ possible combinations of these dimensions:

- *Orientation*: orientation of the plane containing the UI. Can be either "Trasversal" meaning that is parallel to the horizon, or "Frontal", facing the user.
- *Frame of Reference*: frame of reference of the 3 targets. Can be set either as "Ego-centered", in which targets

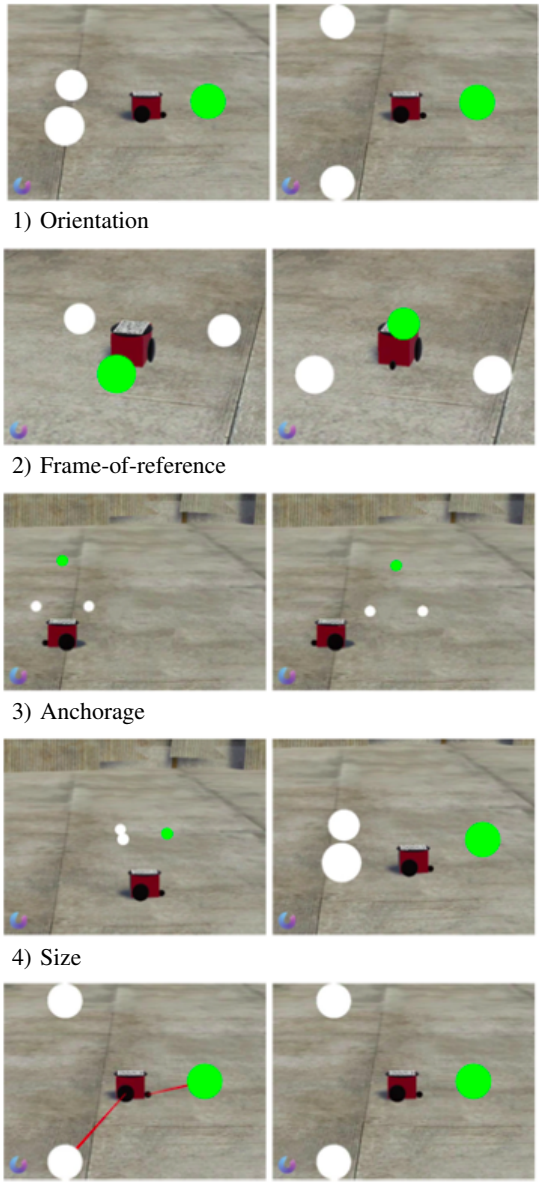


Fig. 5. Layout dimensions able do describe all the possible design strategy scenarios through their combination. For each dimension, from left to right: (1) orientation: transversal, frontal; (2) frame-of-reference: ego-centered, exo-centered; (3) anchorage: anchored (or robot), not-anchored (or user); (4) size: absolute, adaptive; (5) explicitness: explicit, implicit.

correspond to absolute direction and are attached to the user (i.e. when the robot rotates, targets are not rotating with it), or "Exo-centered", attached to the robot (i.e. rotating with the rotation of the robot)

- *Anchorage*: position of the frame of reference in the 3D space. When it is "Anchored", the position of the targets is anchored to the one of the robot (i.e. when the robot moves, the targets are moving with it, even if the robot is no more on the field of view of the HMD), when it is "Not-anchored", the position of the targets is not related to the position of the robot, so anchored to the user position.
- *Size*: dimension relative to the size of the target. In the case of "Absolute" size, targets have fixed dimensions on the 3D space (i.e. the farther the robot is to the user point of view, the smaller the targets will appear). In the "Adaptive" case, the size of the targets in the 3D space adapts to have fixed dimensions on the UI (i.e. the user sees the targets always with the same dimensions). This dimension is expected to have better BCI performances for larger SSVEP targets according to [26], but yet nothing could be concluded about the UI usability beforehand.
- *Explicitness*: explicitness of the association between the targets and the commands. On the "Explicit" case, targets are linked with the robot with corresponding wheels for turning commands and with the front of the robot for the forwarding command. On the "Implicit" case, there is not such link.

2) Subjective Preference on the Targets' Display Strategy: in this user study, the best perceived display strategy is assessed. 42 participants were involved to relatively evaluate the layout strategies on a 7-point Likert scale (Reject, Poor, Acceptable, Satisfactory, Good, Very Good, Excellent) shown in video-clips. Indeed, for each of the 32 display layout strategy, one 24 seconds video-clip has been recorded while the robot was performing the same path but with different strategies combination displayed. The path was made to have an equal number of operations out of the 3 possible ones, and the order of the 32 video-clips was randomized. According to [27] the final qualitative ranking of the strategies came out by a 3-steps process.

1) The majority-grade of a single display strategy is defined as the median grade attributed to that display strategy.
2) A + or - sign is attributed to the major-grade depending on the number of grades that had to be respectively higher (for +) or lower (for -).
3) The majority-gauge is computed. 3 values α, p and q are extracted being them:
   - α the majority grade
   - p percentage of grades *above* the average
   - q percentage of grades *below* the average

   The resulting ranking had to consider the 3 values in this order: α, p and q, from the most preferred one to the least.

Video-clips were assigned to a certain code describing their particular combination of layout dimensions. The code was "DSN" in which DS stands for "Display Strategy" and $N = O*2^4+F*2^3+A*2^2+S*2^1+E*2^0$ with the variables O, F, A, S, E standing for Orientation, Frame-of-Reference, Anchor, Size and Explicitness. The variables could just be assigned to one or zero depending on the implementation of that kind of dimension as shown in *Table I* for clarity.

3) Influence of the Targets' Display Strategy on BCI Performance: four display strategies (DS) were chosen according

TABLE I
RATIONALE BEHIND DISPLAY STRATEGY CODING.

Dimension	1-encoded	0-encoded
Orientation	Transversal	Frontal
Frame-of-reference	Exo-centered	Ego-centered
Anchorage	Robot	User
Size	Absolute	Adaptive
Explicitness	Explicit	Implicit

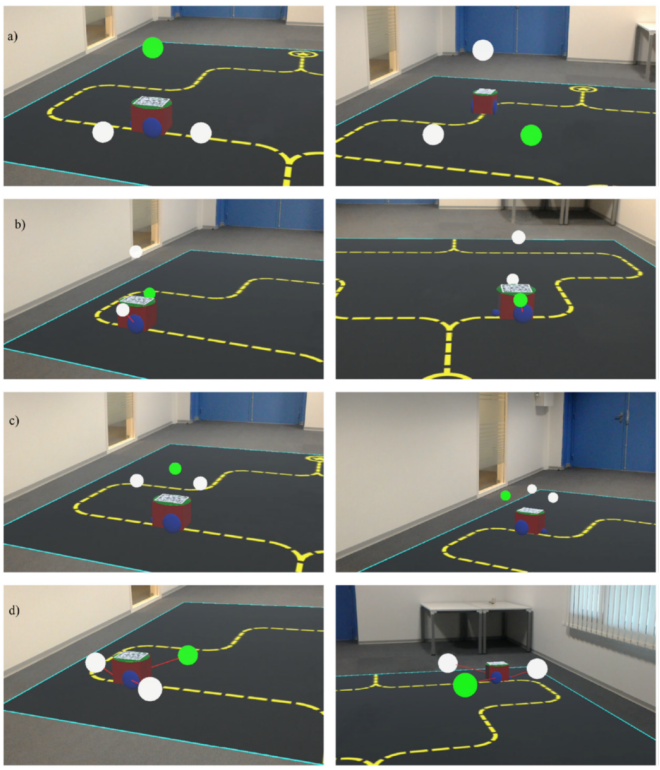


Fig. 6. Strategies used during the fourth user study to assess the performances of display strategies. (a) *DS0*, (b) *DS15*, (c) *DS22*, (d) *DS29*.

to the previous experiment. Those are shown in *Figure 6* and exposed in *Table II* with their respective dimension features.

DS0 has been chosen as a control condition since it is similar to a classical SSVEP training and is expected to maximize the SSVEP response [26]. 24 participants took part to this experiment, EEG headset and OST-HMD setting were the same of the previous user studies. For this experiment, participants had to move the robot through a path marked with a yellow dashed line as shown in *Figure 6* using the BCI commands "go-forward", "turn right" and "turn left"

TABLE II
DISPLAY STRATEGIES SELECTED IN THE FOURTH USER STUDY AND THEIR DIMENSIONS

Code	**Orientation**	**F.-of-Reference**	**Anchorage**	**Size**	**Explicitness**
DS0	Frontal	Ego-centered	User	Adaptive	Implicit
DS15	Frontal	Exo-centered	Robot	Absolute	Explicit
DS22	Transversal	Ego-centered	Robot	Absolute	Implicit
DS29	Transversal	Exo-centered	Robot	Adaptive	Explicit

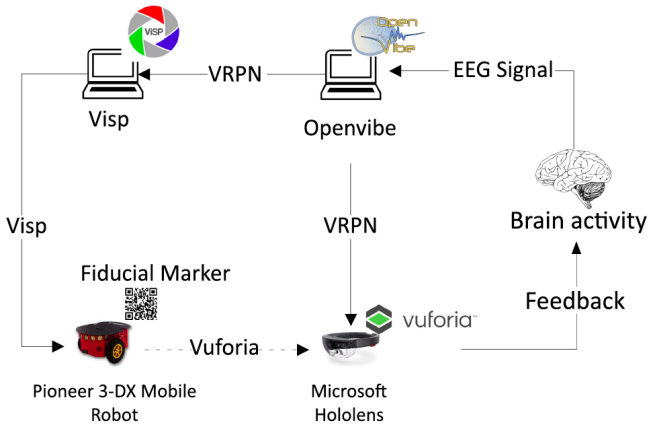


Fig. 7. Hardware and software setting of the final prototype. Brain activity is sent to OpenViBE as EEG signal, that performed an online classification. The results are sent to the HoloLens thanks to VRPN and feedback is displayed. At the same time, VRPN is used even to send results to a running ViSP to control the robot. The robot is always tracked by the HoloLens thanks to Vuforia.

accordingly to the previous studies. The yellow dashed path and the commands were displayed on the HMD. Participants had to accomplish 2 tasks for the experiment. (1) A 7 min training acquisition phase composed by 30 trials as in the first user study (see *Figure 3*): 3 targets flickering at 3 different frequencies arranged as a triangle at 2 m distance from the user. Data gathered was used as in the first user study to train CSP filters and LDA classifiers for each participant with a 7 s trial, 500 ms epoch and an overlap of 400 ms. (2) An evaluation phase consisting in 4 runs of 18 trials each, during almost 4 min. At each run one of the display strategies was assigned randomly and the task consisted of a round-trip of 9 trials. To use the UI, the user had to focus on one of the targets for 7 s. Then, a feedback was provided for 4 s but, since no online classification was done, the feedback was sham as in the training phase. The lack of online classification resulted on the robot always performing the right movement. The objective given to participants to enhance the engagement was to maximize the number of right moves.

C. Final Prototype

A final running prototype was described. Since no user testing has been performed, this review will refer to this part of the study only in this section. The proposed prototype consisted in a set of working hardware and software as shown in *Figure 7*. Brain activity is recorded with an EEG cap and sent to the running OpenViBE software. Here, online classification results are produced and sent through a Virtual-Reality Peripheral Network embedded with OpenViBE to two nodes. One is Microsoft HoloLens OST-HMD to show the real-time feedback into the display. The other node is a ViSP [28] running software, a made-ad-hoc software for controlling visually a robot and embedded with image processing libraries allowing the tracking of visual clues. The controlled Pioneer 3-DX robot was tracked with the help of Vuforia AR tracking

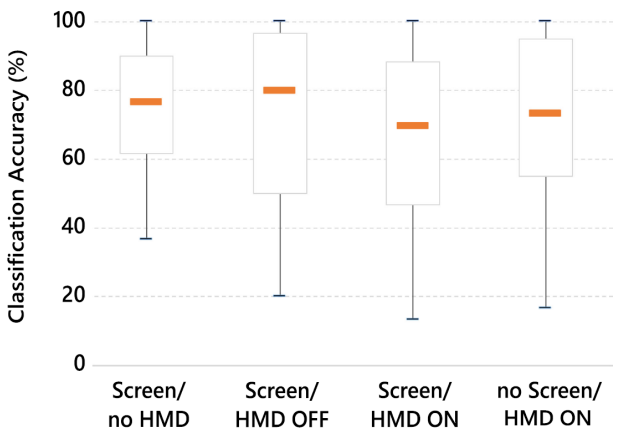


Fig. 8. Results for the first user study concerning external noise. Boxplots are representing the offline classification accuracy for each condition given by the ON/OFF condition of the LCD screen and the HMD.

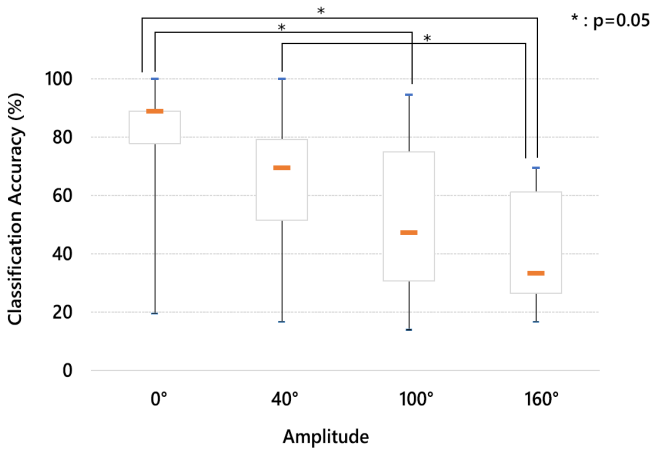


Fig. 9. Results for the second user study concerning internal noise. Boxplots are representing the offline classification accuracy for each condition in terms of amplitude of lamniscates of Bernoulli performed with the head movement. Black lines above are referring to the combinations of conditions for which the null hypothesis has been rejected with the *p-value*, intuitively showing that the two distributions are statistically different (the confidence is in percent $1 - p$).

library and a QR code marker. The commands consisted in 3 SSVEP-based targets: "Forward" was traduced in a forward-speed of 0.2 m/s, "Turn-Right" and "Turn-Left" commands were translated in a rotation of 15 deg/s. All display strategies were possible: however, it was decided to use DS0 as shown in *Figure 6a)* for the informal tests. During these tests, a track was displayed into the OST-HMD as for the last experiment and it was asked to participants to make the robot move through the entire track.

IV. Results

Throughout this section, the results of the user studies are exposed. For this reason, it has the same structure of the previous section, avoiding the part in which the design space was declared, since no experiment was related to it, and the final prototype, since no user tests were performed.

A. Feasibility Study

1) Influence of AR Device on BCI Performance: given 4 conditions, it was performed a non-parametric test for paired samples, a Friedman Test. This was done to test the null hypothesis H_0 = there is no statistical difference between the conditions. The research group considered the number of samples as relatively high, therefore a χ^2 distribution was used as approximation with 3 grades (4 runs - 1) of freedom. Results showed no significant difference between the runs:

$$\chi^2(3) = 5.025, p - value = 0.170$$

Results are summarized in *Figure 8*.

2) Influence of Users' Movements on BCI Performance in AR: the results on the offline classification accuracy showed a clear degradation of the BCI performance as the head movement increased. Results can be found in *Figure 9*. From 78 percent in the case of not moving, performance dropped to 41 percent in the "High-Intensity Movement" (160°). A Friedman test was performed as in the previous experiment, resulting in rejecting the null hypothesis and so with a statistical relevance on the difference of the distributions at 95 percent of confidence. Following these results, a Post-Hoc test between all the conditions after Friedman test was performed to see where these differences reside. Using a null hypothesis H_0 = there is no statistical difference between the two conditions with $p - value = 0.05$ considering all the possible condition couples, the results showed no relevant difference on the condition pairs:

- No Head Movement and Low-Intensity Head Movement
- Medium-Intensity Head Movement and High-Intensity Head Movement

So rejecting the null-hypothesis for all the other combinations.

B. A Design Space for BCI-Based User Interfaces in AR

1) Subjective Preference on the Targets' Display Strategy: results can be clustered into 4 groups according to "Orientation" and "Frame of Reference" dimensions. Transversal and Exo-centered dimensions had better results (codes between 24 and 31) always with Good as majority grade, followed in order by: Frontal + Exo-centered (codes 8-15) with Satisfactory as majority grade, Frontal + Ego-centered (codes 0-7) and Transversal + Ego-centered (codes 16-23). These last two groups have both Poor and Acceptable majority grades. Some relevant results can be found in *Table III*.

2) Influence of the Targets' Display Strategy on BCI Performance: the results of the experiment can be found on *Figure 10*. As for the other experiments, the non-parametric Friedman test was performed with the approximation of the χ^2 distribution with 3 degrees of freedom. The Friedman test showed a relevant effect of the proposed display strategy with respect to DS0, the control one:

$$\chi^2(3) = 12.23, p - value < 0.01$$

Significant statistical difference with $p - value < 0.05$ was found between display strategies DS0-DS15 and DS0-

TABLE III
RESULTS OF SOME RELEVANT STRATEGY DURING THE THIRD USER STUDY EVALUATING INDIVIDUAL PREFERENCE ON THE COMBINATIONS OF DISPLAY STRATEGIES.

Majority Ranking	Display Strategy #	p % above α	$\alpha\pm$ Majority Grade	q % below α
1	29	48%	Good+	17%
2	30	45%	Good+	31%
3	31	43%	Good+	29%
6	24	33%	Good-	33%
9	15	33%	Good-	45%
11	9	48%	Satisfactory+	33%
16	0	31%	Satisfactory-	50%
17	13	48%	Acceptable+	31%
19	22	33%	Acceptable-	43%
23	4	45%	Poor+	24%
32	19	38%	Poor-	45%

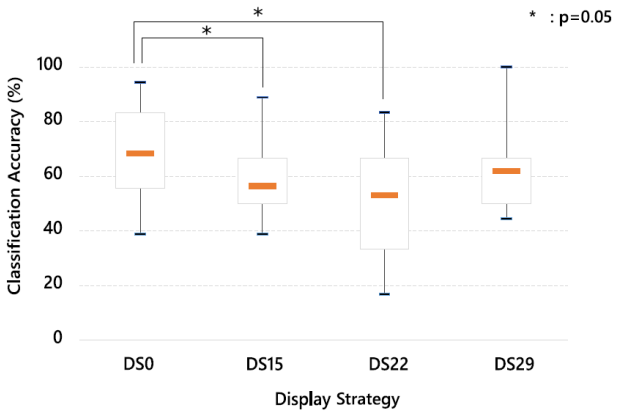


Fig. 10. Results for the fourth user study concerning the influence of the display strategies on BCI performances. Black lines above are referring to the combinations of conditions for which the null hypothesis has been rejected with the *p-value*, intuitively showing that the two distributions are statistically different (the confidence is in percent $1 - p$).

DS22. Mean accuracy results of all participants on all display strategies has been equal to 45 percent.

V. DISCUSSION

This section goes through the results of the paper providing insights and literature comparisons to interpret the scientific findings. Before dealing in detail with all the results of *the study*, a brief discussion about the related work is provided. As the authors of the reviewed paper pointed out, not many other feasibility studies about the AR-BCI blend were made at the time of the writing. This can be the reason why the number of the scientific studies that are citing *the study* on their respective scientific literature reviews is relevant. The papers that are citing *the study* use that as proof of feasibility of the AR-BCI blend or as benchmark on the accuracy levels that can be reached. Not much has been used by relevant scientific papers on the head movement part, or the design part. While for the head movement it is possible to conclude that the results are not numerically promising (see later for details), it is likely that the latter topic, the design one, is not used since it could have more commercial applications rather than scientific. It is more expected that one commercial application uses the design findings of this document rather than a scientific study. Lastly, the research group did not proceed on the wave of these findings but rather changed a bit the focus as in [29] in which this time the blend between BCI and Virtual Reality is addressed or [30] in which no MR technology is used.

A. Feasibility Study

On the first user study, the 4 runs have no significant difference, with classification accuracy between 75 and 80 percent. This was predicable according to [16] blending AR (77 percent) and other literature that does not consider AR but just BCI [31] (84 percent in 1 sec stimulus), [32] (84 percent for 2 sec stimulus). During the second user study a deterioration of classification accuracy has been reported as the head movement increased. This is in line with [33] and [34]. Higher intensities on head movement have worse results but above chance level that in this case according to [35] are around 45 percent. This makes it clear that the relevant problem comes in the cases of middle and high intense head movements. This narrows down the possible application domain of the blending of BCI and AR. Since many of the experiences on the whole Mixed Reality field rely on relevant head movement, those can not be blended with BCI for scarce performances.

B. A Design Space for BCI-based User Interfaces in AR

The third study showed that participants preferred transversal orientation, namely the UI lays on the horizon plane. Even exo-centered frame of reference has been preferred comparing to the ego-centered type. Therefore most of participants preferred to see the targets rotating as the robot was rotating. A reason could be that this setting minimizes the number and the complexity of mental rotations to move and rotate the robot especially in the cases in which the robot is not directed forward with reference to the user. The intent of the fourth user study was to compare the results of the third user study, relative just to user preference, to BCI performances. According to [26] size of the targets is relevant on BCI performances. This could be the reason why *DS0* and *DS29* had better results related to the other two cases thanks to their adaptive size: users that saw targets with fixed dimensions on the UI reported better performances. Furthermore, *DS29*, the most preferred display strategy by users, has not relevant deterioration on BCI performances using *DS0* as control case. This section ends with a recommendation on displaying the targets in a transversal way and with an exo-centered frame of reference: both from a user preference point of view and a BCI performance one. This result could be useful for many applications on the AR-BCI blending, and the proposed designed space is valuable according to the study, since the most preferred design space is even good for what concerns BCI performances.
However, as already pointed out, no further studies has been made by the group or no relevant studies have been done on the design of AR-BCI blend since *the study*, even if the research of the design spaces in immersive spaces like MR, AR or VR seem to be active for many different applications. See [36] for an example of a design space for AR in car driving, or

[37] for a design space for 3D sketching in virtual reality. The reason is likely to be that technology has evolved and now OST-HWDs are cheaper and come with always more improved features such as gaze tracking embedded with themselves like in the case of [38] so SSVEP at first sight could seem dated, preferring eye-gaze for having a more reliable result than SSVEP as for [39]. The new researches are therefore more focused on the eye-gaze rather than SSVEP. However, nothing has been said for Event-Related-Potentials (ERPs): those could be used for example with visual-audio events, or just audio [40]. The latter could be used even by people that can not see, allowing them to interact to the surrounding, eventually augmented, environment.

VI. Conclusions

In this document, [1] has been reviewed. The user experiments presented during *the study* has been exposed in detail thinking to a moderate background audience on scientific fields.

THE introduction about the technologies used by the reviewed paper is the very first topic shown throughout this document which has shown, other than addressing the modalities of Augmented Reality, a brief overview about Brain-Computer Interfaces covering SSVEP and how to use this kind of interface: lastly, an introduction about *the study* is provided.

Then, a scientific review of the literature is made. This is structured showing both the context in which the reviewed paper was at the time of the writing and the development that *the study* had on the scientific community. At the time of the publication of the reviewed paper not many papers were studying the actual feasibility of the AR-BCI blending, especially from the point of view of design and UI. This underlines the importance of the study for the scientific community.

Afterwards, *the study* is addressed, starting with the feasibility of the blending of AR and BCI. According to the findings, there is no relevant problem on the external noise or on internal noise in low-intensity head movements but not-negligible problems arise with middle and highly intense head movements.

Therefore, the proposal of a design space is addressed. That is based on the definition of 5 dimensions: *Orientation, Frame of Reference, Anchorage, Size, Explicitness*. Those are evaluated both as an intuitive preference from the participants of the experimental study and compared with BCI performances. Results showed that the most preferred display strategy was even one of the most valuable from a BCI performance point of view.

As a future development of this work, it could be interesting going deep on the possible head movement to understand what are the maximum head movement tolerated by the blending. Another interesting topic is the User Interface one, especially for the case of ERPs used with audio events, finding design strategies that could be valuable from a usability and BCI performance point of view to enhance the value brought by the AR-BCI blending to the users.

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