



HAL
open science

Towards electrophysiological measurement of presence in virtual reality through auditory oddball stimuli

Emile Savalle, Léa Pillette, Kyungho Won, Ferran Argelaguet, Anatole Lécuyer, Marc J-M Macé

► To cite this version:

Emile Savalle, Léa Pillette, Kyungho Won, Ferran Argelaguet, Anatole Lécuyer, et al.. Towards electrophysiological measurement of presence in virtual reality through auditory oddball stimuli. *Journal of Neural Engineering*, 2024, 21 (4), pp.046015. 10.1088/1741-2552/ad5cc2 . hal-04672526

HAL Id: hal-04672526

<https://hal.science/hal-04672526v1>

Submitted on 19 Aug 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Copyright

Towards Electrophysiological Measurement of Presence in Virtual Reality through Auditory Oddball Stimuli

Emile Savalle¹, Léa Pillette², Kyungho Won¹, Ferran Argelaguet¹, Anatole Lécuyer¹, Marc J-M Macé²

¹Inria, Univ. Rennes, IRISA, CNRS – F35000 Rennes, France.

²Univ. Rennes, Inria, CNRS, IRISA – F35000 Rennes, France.

E-mail: emile.savalle@inria.fr

January 2024

Abstract. Objective. Presence is an important aspect of user experience in virtual reality. It corresponds to the illusion of being physically located in a virtual environment. This feeling is usually measured through questionnaires that disrupt presence, are subjective and do not allow for real-time measurement. Electroencephalography (EEG), which measures brain activity, is increasingly used to monitor the state of users, especially while immersed in virtual reality. **Approach.** In this paper, we present a way of evaluating presence, through the measure of the attention dedicated to the real environment via an EEG oddball paradigm. Using breaks in presence (BiP), this experimental protocol constitutes an ecological method for the study of presence, as different levels of presence are experienced in an identical virtual environment. **Main results.** Through analysing the EEG data of 18 participants, a significant increase in the neurophysiological reaction to the oddball, i.e., the P300 amplitude, was found in low presence condition compared to high presence condition. This amplitude was significantly correlated with the self-reported measure of presence. Using Riemannian geometry to perform single-trial classification, we present a classification algorithm with 79% accuracy in detecting between two presence conditions. **Significance.** Taken together our results promote the use of EEG and oddball stimuli to monitor presence offline or in real-time without interrupting the user in the virtual environment.

Keywords: Virtual reality, Presence, Brain-Computer Interfaces, EEG, Event-Related Potential, Oddball paradigm, Attention

1. Introduction

Presence is a state of consciousness that arises when one is immersed in a virtual environment. A high level of presence in a virtual reality (VR) environment has a positive effect on distinct behaviors. Users feeling present in a VR environment (i) react to stimuli as if they were real, (ii) are more involved and efficient in VR-related tasks, (iii) are more attentive to events occurring in the VR environment, and (iv) globally retrieve a better experience from VR exposition [1, 2].

The reasons why presence is achieved, or not, are still not fully understood, and a wide range of internal and external factors from the virtual environment have been shown to modulate the overall perceived presence [3], such as the degree of realism [4] or the coherence of the experience [5]. Additionally, presence can be disrupted by several external events such as unexpectedly touching a physical object or experiencing rendering issues or due to technical difficulties. These events, qualified as “Breaks in Presence” (BiP) [1], occur when the participant stops responding to the virtual stream of information and resumes responding to the sensory stream from the real world. BiPs have a negative impact on presence [1].

An additional challenge while studying presence is its precise assessment [6]. The assessment methods must have enough sensitivity in order to discriminate subtle differences in presence, and if possible, detect those potential breaks in presence that can arise during a virtual experience. In addition to the pure assessment of virtual experiences, being able to adjust the level of presence in a virtual experience is important for a wide range of applications. For instance, in virtual reality therapies for phobias, the ability to control and gradually increase the level of presence allows therapists to create a safe and controlled environment where patients can gradually confront their fears, aiding in the therapeutic process [7].

While a wide range of measurements of presence has been explored [5], the most common method still remains the use of questionnaires [6, 8], such as the iGroup Presence Questionnaire [9] or the Slater-Usch-Steed Questionnaire (SUS) [10]. While presence questionnaires are not dependent of the virtual environment and can be compared among different virtual experiences, in order to respond to these questionnaires users have to interrupt the immersion in the virtual environment and they are typically

administered at the end of the experience. Thus, the responses only represent a global perception of the level of presence and not a detailed time-course. Moreover, these measures can sometimes be unreliable [11], as the concept of presence can be cryptic to participants, and is subject to high inter-individual variability, as they can be influenced by the participants’ prior experiences in user studies [12].

The use of neurophysiological measures is a promising method to assess presence in VR, as it allows a measure of the mental states of the user without disturbing their experience. It has been used in VR to assess user experience factors, such as the level of agency over an avatar [13], application errors [14] or cognitive workload [15, 16]. Regarding presence, previous studies explored measuring presence using electroencephalography (EEG) via neuromarkers related to attention [17, 18, 19, 20] since it is related to the level of presence [21]. Indeed, when users are present in a VR environment, they are gradually paying less attention to the real world. Thus, having a measure of that shift in attention from real to virtual environment could be used as a proxy to measure presence in VR.

To that extent, past studies relied on an oddball paradigm which is commonly used to monitor attention and consciousness through the observation of the amplitude of electrical brain responses that are time-locked to specific events or stimuli [22, 15], named, event-related potentials (ERPs). The oddball paradigm consists in exposing the user to a series of identical stimuli (e.g. sounds), with an infrequent and random insertion of a divergent stimulus called deviant. When observing the participant’s reaction to these deviant stimuli, mainly using EEG, we can monitor a deviation in the signal reflecting the attention allocated toward these stimuli. However, the precedent studies that used the oddball paradigm to measure presence [17, 18, 19, 20] did not analyze the P300 response. The P300 response is classically the main component studied in the oddball paradigm, as its amplitude is strongly correlated to the attention allocated toward deviant stimuli [23, 24, 22, 25].

In this paper, we explore the use of the oddball paradigm to measure presence, by evaluating the user’s attention to external stimuli while being immersed in a virtual environment using a head-mounted display (depicted in Figure 1a). Using BiP, we intentionally negatively impacted the presence felt by the participants, in order to have two experimental

conditions producing different levels of presence within the same environment. Through EEG data analysis, we observed a difference in the reaction to the oddball paradigm based on the experimental conditions, where lower presence produces stronger reactions to the oddball stimulus. This difference, observed in the P300, represents the shift of attention between real and virtual environments. P300 amplitudes are negatively correlated with self-reported measure of presence (obtained through questionnaires). Additionally, we used the EEG data to train a Riemannian geometry-based algorithm, capable of correctly classifying the presence conditions with an accuracy of 79% . In summary, BiPs are here used for the first time to produce an ecological environment for a neurophysiological measure of presence, observing through the P300 the change in attention toward the real environment coming from a change in presence. Additionally, we present evidence that questionnaires and this neurophysiological marker provide compatible measurements.

2. Related Work

In this Section, we present the different methods that can be used to measure presence. First, we describe the most traditional approach, which is questionnaire, as well as behavioral measures. Then, we detail neurophysiological measures of presence, with special attention to the oddball paradigm.

2.1. Behavioral and self-reported measures of presence

Traditionally, presence has been measured through questionnaires. Souza & al. [6] provided a comprehensive review of the methods employed to measure presence, and reported that an overwhelming majority of studies used questionnaires. Through questions asked to the user after a virtual experience, questionnaires allow a simple and cost-effective measure of the different components of presence (spatial presence, involvement,...), while providing standardized metrics facilitating comparisons across studies. However, these questionnaires can be unreliable due to the subjective nature of self-report measures and since presence is a relatively unfamiliar concept to the general public[11]. Also, questionnaires are inherently incompatible with a real-time measurement, since asking questions about presence in VR forces the user to stop their VR task to assess their current state, thus breaking their feeling of presence.

Behavioral measures can also provide valuable information about presence in VR, such as the level of engagement, exploration, or interaction within the virtual environment. For example, researchers can observe users' navigation patterns, task performance, or their reaction to an unexpected event [26]. This is

based on the assumption that as participants experience a higher level of presence in the virtual environment (VE), their reactions to virtual stimuli will tend to become similar to their reaction to a natural stimulus. These measures could be more reliable than subjective measures, without impacting presence. Though, a change in behavior can occur independently of a change in presence [6].

2.2. Neurophysiological measurement of presence

The use of neurophysiological measures is steadily increasing in VR, as it provides objective and continuous assessments of VR users' mental states. For the measurement of presence, different frequency components of the EEG have been studied, such as alpha rhythm [27], as those features have been closely associated with attention. Kober[27] studied the feeling of presence by comparing two VR systems, Single-Wall-VR-system (three-dimensional view, large screen) and a less immersive Desktop-VR-system (two-dimensional view, small screen). They observed a significant correlation between alpha power and their presence conditions, where an increase in the sense of presence, produced by a more immersive VR system, was accompanied by an increased parietal task-related power decrease (TRPD).

2.3. Oddball paradigm for the measurement of presence

2.3.1. The oddball paradigm

Additionally, the oddball paradigm has been investigated as a potential tool to obtain an objective measure of presence. It is a neuro-scientific exploration method, in which a participant is presented with a repetition of stimuli [28, 22]. Since the oddball paradigm can act as a measure of attention, it has been used in a few studies as a mean of indirectly measuring presence, by producing the stimulus in the real environment to measure the shift in attention from the real to the virtual environment, a sign that a user is present in the virtual environment. In the typical two-stimuli oddball, a series of standard stimuli (visual, tactile or auditory) is presented to the participant at a fixed rate, and a different stimulus (deviant) randomly and infrequently replaces a standard stimulus. Brain activity measures (EEG, magnetoencephalography (MEG)) show that an automatic reaction to deviant stimuli can be observed. The randomness of the occurrence of the deviant is important to prevent any expectation of its appearance and trigger the reaction.

The oddball paradigm can be used for active or passive experiments. In active experiments, participants are asked to focus on the oddball stimulus and react to them, traditionally by counting or signaling the occurrence of a deviant stimulus [29, 30]. In passive

oddball paradigm, participants are asked to complete an unrelated task while being subjected to oddball stimuli [31, 32, 33, 34]. In contrast to active oddball, participants are not asked to react or be attentive to these stimuli.

In a traditional EEG two-stimulus oddball experiment, two main ERP components are traditionally studied, the Mismatch Negativity (MMN) and the P300.

The P300, in the context of the oddball paradigm, is a positive peak occurring between 250 and 400 ms [33] produced in reaction to an unexpected deviant stimulus. The rarity of the deviant stimulus greatly impacts this ERP, producing higher amplitude when intervals between deviants are increased [23].

The MMN, is a negative peak observed between 100 and 250- ms [19] observed in the waveform obtained by subtracting the reaction to the standard stimulus from the reaction to the deviant one. It is also elicited in reaction to the oddball paradigm and the perception of deviant stimulus, and reflect the automatic auditory processing [35].

In passive oddball paradigm, studies mostly focus on the MMN as it reflects the brain’s ability to automatically perform comparisons between stimulus. However, due to its high correlation with attention [23], and its presence in passive oddball paradigm [31, 33], the P300 is a worthwhile ERP component to study in this context.

These two ERPs can be impacted by attention, as the P300 amplitude is linked to the attention allocated toward the oddball stimulus [23] and the MMN may not be produced if the auditory change produced by the deviant isn’t perceived or if there isn’t enough attentional resources available for its evaluation [35]. So, in a dual-task or passive oddball paradigm, when the main task increases in complexity, thus requiring more attentional resources to be processed, a decrease in the proportion of attentional resources allocated to the processing of the oddball stimuli can be observed through the measure of ERPs. Thus, the oddball paradigm allows a measurement of the attention required by a primary task.

2.3.2. Measuring presence with an oddball paradigm

The oddball paradigm has been introduced in the field of virtual reality to measure presence through the attention allocated towards the real environment in three different studies [18, 19, 20] thus acting as a proxy measure for presence. In these studies, participants experienced a single virtual environment, displayed on a head-mounted display, while being subjected to auditory oddball stimuli played on loudspeakers located in the real environment. Their presence levels were assessed through questionnaires and used during data processing to divide the participants into two presence

groups (one of high presence, and one of low presence). Each of the three studies found a significant difference in the brain reaction to the oddball based on those presence groups, namely around the ERPs N1 [20, 19] and slow-wave 1&2 (SW) [18, 19, 20].

Burns et al. [17] also used an oddball paradigm in VR to assess presence. Their goal was to study the impact of the difficulty of a video game on presence. Their participants played a racing video game with different levels of difficulty while oddball sounds were played in the background. Their analyses of 3 ERPs (P1, SW and late negativity (LN)) indicate that presence is negatively impacted when the game difficulty is low, and that an adapted difficulty helps build the feeling of presence.

However, they split their data into presence groups based on responses to presence questionnaires, preventing any results showing a difference for each participant during the VR experience.

Thus, the previous work suggesting the viability of using an oddball paradigm to assess presence level could not evaluate presence variations within participants in the same environment.

3. Materials and methods

In this study, we used an oddball paradigm as a method to objectively assess presence using electroencephalographic measurements. All participants experienced two different experimental conditions in a virtual environment presented through a head-mounted display. With the passive oddball paradigm and the evaluation of its event-related potentials, we aimed at measuring the user’s attention to the real world in these two conditions. Due to the correlation between attention to the real environment and presence, we expected to measure a difference in attention reflecting the level of presence of the user.

3.1. Participants and apparatus

Twenty-four participants (11 women, 13 men) took part in the experiment (average age = 32; std = 8.9). Before signing a consent form, all the participants were instructed about the topic and course of the experiment as well as their rights during and following the experiment, such as their ability to stop at any time. The experiment was validated by Inria’s ethical committee (agreement n°2022-45).

3.2. Experimental protocol

The experiment comprised a unique session lasting about one hour. Before starting, participants were briefed about the course of the experiment and instructed to keep their head straight and limit as

much as possible their movements, to limit noise contamination in the EEG signal. Then, the EEG cap was placed on their head.

They were first familiarised with the oddball stimulus used during the experiment (see Subsection 3.2.3) with a preliminary control trial during which they were subjected to 7 minutes of these stimuli while their brain activity was recorded without the VR headset. Then, they experienced a walk in a VR environment (see Subsection 3.2.1) during two different conditions (see Subsection 3.2.4). One condition included frequent BiP to impact the user’s feeling of presence, while the other condition didn’t (see Subsection 3.2.2). During these two conditions, participants were asked to not actively pay attention to the oddball stimuli. The timeline of the experiment is depicted in figure 2

3.2.1. VR Environment

The virtual environment consisted in a forest where the participants passively walked (Figure 1.b). They were embodied in a character resembling them in terms of gender and color. Participants observed it briefly before starting the experiment. During each trial, the character walked in the forest and the users were able to feel it by hearing the footsteps and observing their displacement, consistent with a normal walk. Only the head movements of the participant were transmitted to the virtual avatar, but participants were asked to limit their head movements to prevent any artifacts in the EEG data. This virtual environment was designed to induce presence and limit cybersickness as much as possible. The virtual environment was designed and presented using Unity VR software and C# scripts. The experimental protocol has been produced with OpenViBE and relied on TCP for communication with Unity.

A few objects (i.e., 9 mushrooms and 9 statues of cats) were hidden in the forest, and the participants were instructed to count them, and report how many they saw at the end of their walk. The performance in this task was irrelevant; it was implemented solely so that the participants were focused on the virtual environment to improve the feeling of presence.

3.2.2. Breaks in Presence

In this study, we aimed at measuring different levels of presence, so we intentionally (negatively) impacted the feeling of presence of the participants. Using the external camera of the HTC Vive HMD (Head-Mounted Display), we broke presence by displaying the real surrounding room inside the headset (Figure 1.c). When presented for 2 seconds, this interruption produced a drastic setback to reality. The users are reminded of their condition of participant in a VR experiment, thus heavily impacting their feeling of

presence. There are other ways to impact presence, such as changing textures and details of the environment [36], the discrepancy between the user’s virtual and physical head pose [37] or the embodiment of the virtual character [38]. However, our goal was to keep the two conditions as similar as possible and to limit the impact on other factors of the user experience, such as cybersickness.

3.2.3. Auditory oddball stimuli

During the two conditions, the participants were subjected to oddball stimuli. We used two audio stimuli, a 100 ms pure tone sound (1000 Hz for the standard, 2000 Hz for the deviant) played on loudspeakers placed roughly 50 cm behind the participant. We used external speakers (rather than the built-in HMD speakers) so that participants associated the oddball stimulus with the real environment rather than the virtual one. These sounds were delivered at a rate of 1 per second throughout the trials, only stopping during the breaks in presence. Deviants represented 15% of all sounds played; their sequence was pseudo-random with no direct repetition, preventing the occurrence of two consecutive deviants.

3.2.4. Conditions

The experimental protocol was designed in two parts. First, participants experienced a preliminary control trial where they experienced only the oddball stimulus without a VR headset, in order to assess the validity of the oddball paradigm and familiarize participants with these stimuli. Then, using BiP, we designed two experimental conditions, to induce different levels of presence for the participants:

- **Without_BiP:** Users are passively walking in a virtual forest, without any BiP.
- **With_BiP:** Users experience the same walk, but with numerous BiP occurring, at a rate of 1 BiP every 30 s.

Each condition was composed of a single trial, which involved a 7-minute walk, and participants experienced both conditions. The order of presentation of these two conditions was counterbalanced across participants.

3.2.5. Questionnaires

At the end of each experimental condition, participants were asked to fill in the iGroup Presence Questionnaire. The questionnaire was presented inside the virtual environment, and participants had to answer through a 7-point Likert scale, where positive values represent a higher presence, and negative values a lower presence. This questionnaire was used to assess presence between conditions in a more traditional way. It provides four main indications:



Figure 1: Experimental setup. Left: The user, equipped with the VR headset (1) and EEG cap (2), and the loudspeakers (3) producing oddball stimulus. Middle: Virtual environment developed to induce presence. Right: User’s view during a Break in Presence showing in real-time the real environment within the headset.

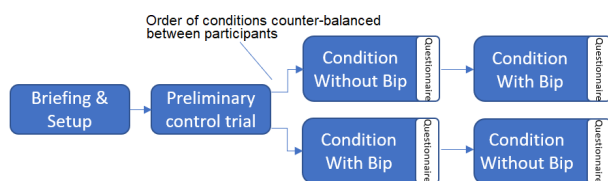


Figure 2: Timeline of the experiment.

- General Presence (PRES): the general sense of ‘being there’ felt by participants
- Spatial Presence (SP): how much participants felt physically present in the VE.
- Involvement (INV): how much participants were involved and paid attention to the VE.
- Experienced Realism (REAL): how realistic did participants feel their experience was in the VE.

3.3. Neurophysiological measurement & Signal Processing

3.3.1. Recording

The EEG data was recorded using an ANT Neuro system (Eego sports, ANT Neuro, The Netherlands), composed of 32 electrodes (Fp1, Fpz, Fp2, F7, F5, Fz, F4, F8, FC5, FC1, FC2, FC6, C3, Cz, C4, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, POz, M1, M2, T8, T7, O1, Oz, O2) positioned accordingly to an extended 10-20 system and filled with non-abrasive electrolyte gel. The EEG data was referenced to CPz and grounded to AFz. The signal was recorded at 500 Hz through OpenViBE [39] (an open-source brain-computer interface (BCI) software) and re-referenced to P7-P8 due to the original reference electrode (CPz) being located in the region of interest of this study. P7-P8 have been selected for being the most stable electrodes outside the region of interest, as mastoids weren’t consistent in all recordings due to noise and artifacts.

3.3.2. Preprocessing

EEG data has been preprocessed with MNE-Python [40]. The signal was filtered with a Finite Impulse Response (FIR) band-pass filter, providing a stop-band attenuation of approximately 53 dB, with cut-off frequencies of 2 and 20 Hz to reduce the effects of environmental noise, drifts, motion artefacts, etc. We used an independent component analysis (ICA)[41, 42]. The ICA decomposes the EEG data so that the independent components are maximally independent. In terms of non-brain activity, it is known that eye blinks and muscle activities can be easily identified, as they produce ICA components with specific patterns and component maps[43]. In this regard, we selected noise components by visual inspection based on frequency (high-frequency activity is often linked to muscle movements), and temporal and spatial patterns (i.e. short burst of frontal activity is usually produced by eye movements). Due to the low amount of EEG channels used, only clear artefactual components (high-frequency activity, clear temporal and spatial patterns) were removed, resulting in 0 to 2 components per participant removed. We extracted epochs from -200 to 1000 ms to the auditory stimulus onset, and the extracted epochs were baseline-corrected with the first 100 ms. Additionally, epochs with amplitude greater than $\pm 70 \mu\text{V}$ were rejected as noisy epochs. As a result, 4 participants were rejected due to an important presence of artefacts in the data (over 40% of epochs rejected), and 2 due to noisy signal on electrodes of interest (particularly Cz). This signal preprocessing is applied for each of the following analyses.

It should be noted that this oddball paradigm design and EEG signal preprocessing correspond to a standard approach, that has been used in several experiments [18, 20, 19, 17, 28].

3.4. Variables, Factors & Statistical Analysis

3.4.1. Questionnaire

To evaluate the impact of the BiP on the feeling of presence experienced by the participants, we investigated the self-reported measure of presence. The answers to the iGroup Presence Questionnaires were aggregated by categories (General Presence, Spatial Presence, Involvement, Experienced Realism) and then compared between `WITHOUT_BIP` and `WITH_BIP` conditions through Wilcoxon signed rank test, chosen due to the non-normality of the data. This test evaluates the statistical significance of the change in the reported feeling of presence, particularly to investigate whether BiP significantly affected the subjective perception of presence in VR.

3.4.2. Neurophysiological analysis

We studied the impact of the experimental conditions on the neurophysiological responses to the oddball paradigm. Our analysis of the EEG data focused on the reaction to the deviant stimuli, which present information about the attentional resources allocated towards the processing of the stimuli, notably for the P300.

ERP analysis We then analyzed the grand-averaged reaction to the deviant stimulus in both conditions to observe the spatial and temporal differences in our signal. We averaged the EEG signals for both conditions from 0 to 500 ms post-stimulus and performed paired t-test comparison for each time point (501 samples between 0 and 1000 ms) and electrode to assess the statistical significance of the differences.

The electrophysiological analysis aimed at measuring the impact of the experimental conditions on the ERP associated with the oddball paradigm, mainly on the P300 and the MMN. Our analysis focuses on electrode Cz, as P300 is observed around the centro-parietal network and is a commonly used channel in the P300 literature [23], but, as the electrodes Fz and Pz are also investigated in the oddball literature [28, 22], we've duplicated the following analysis on Fz and Pz and added the figures in Supplementary Material (Figure 8 & 9).

To measure these ERPs, we calculated the amplitude of the maximum positive peak of the signal between 250 and 400 ms for the P300 (as in [33]) and the maximum negative peak between 100 and 250 ms in the deviant - standard waveform for the MMN (as in [44]), at the electrode Cz and then averaged per participant for each reaction to the deviant stimulus, providing a single averaged amplitude per subject per condition. In order to analyze the statistical significance, we used a repeated-measure ANOVA to assess the difference in amplitudes between ERPs.

For the study of the MMN, we subtracted the average response to the standard stimulus to the average response to the deviant to get the deviant - standard waveform.

3.4.3. Correlation between self-reported and neurophysiological measurements of presence

We investigated the relationship between self-reported measures and the neurophysiological responses in order to assess the coherence between these two measures of presence. To assess the link between questionnaire responses and reaction to the oddball, we computed the correlation between the responses from significant factors of the questionnaire with the corresponding averaged amplitude of the P300 and MMN, through a Pearson test, reporting the correlation coefficient and its significance.

3.4.4. Single trial classification of presence

Finally, to assess the possibility of a real-time measurement of presence, we developed a single-trial algorithm aiming at classifying the experimental context based on the EEG data. For the classification of `WITHOUT_BIP` and `WITH_BIP` conditions, we used the whole signal, from stimulus onset to 1000 ms post-stimulus from both conditions on all electrodes, with an average of 53 data samples per condition per participant, yielding feature vectors with the dimension of [53 x 30 x 500], which represents the number of trials, channels, and samples, respectively.. We used the pyRiemann library [45] to model a classifier based on Riemannian geometry. We first calculated covariance matrices from the filtered EEG signal using XDAWN spatial filtering, an effective specialized covariance matrix for ERP analysis [46]. These matrices are then projected in the tangent space using Riemannian geometry and classified between conditions with logistic regression. Classification performance was estimated using 5-fold cross-validation repeated 10 times. For 5-fold cross-validation, the data were divided into 5 folds. Then, one fold was used as a test, and the other four folds were used for training.

The classification results are reported in terms of accuracy (number of samples with the correct experimental context determined), true positive rate (TPR) and true negative rate (TNR) where `WITHOUT_BIP` conditions are considered as positive and `WITH_BIP` as negative. The chance level was evaluated to be at 62% for a 0.05 significance level based on the results of Muller-Putz and al. [47].

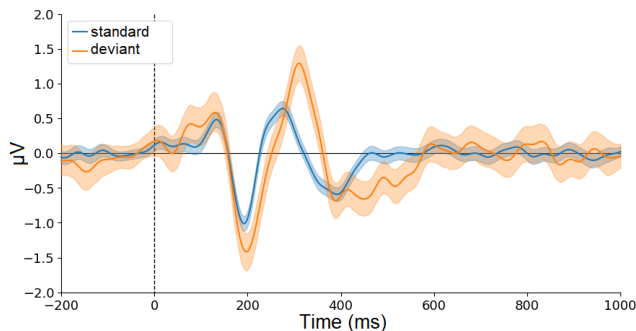


Figure 3: Grand-average waveform for the standard and deviant stimuli across conditions (Cz electrode) with standard deviation across the means of the participants.

4. Results

4.1. Protocol validation

4.1.1. Questionnaires

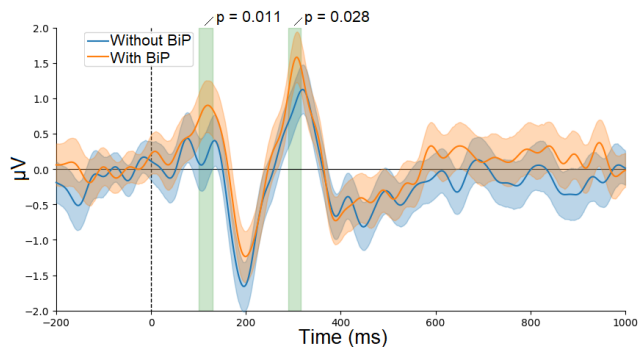
First, for the study on the impact of BiP on the feeling of presence experienced by the participants, we compared the self-reported questionnaires from both WITHOUT_BiP and WITH_BiP presence conditions. Subjects reported overall a higher feeling of presence in the WITHOUT_BiP condition, depicted in Table 1. As stated in Subsection 3.4.1, Wilcoxon signed ranked tests were performed to assess the statistical significance of these differences. A significant difference was found for the Involvement component of the questionnaire, which represents how involved people felt and how much attention they paid to the VE ($Z = 58$, $p = 0.013$).

Table 1: Average Response to the iGroup Presence Questionnaire. Results for the different factors (PRES = General Presence, SP = Spatial Presence, INV = Involvement, REAL = Experienced Realism) per experimental condition, reported as average value with standard deviation. The last column contains the p-values of the Wilcoxon signed ranked test comparing our experimental conditions.

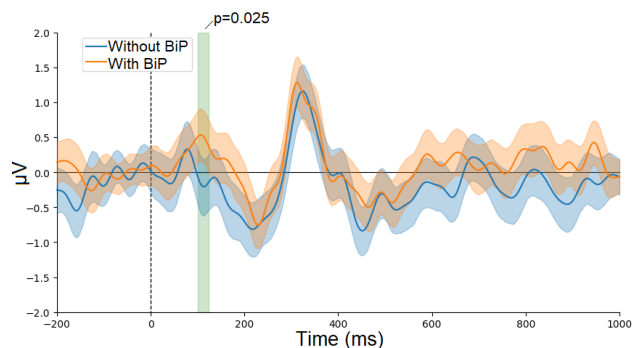
Group	WITHOUT_BiP	WITH_BiP	p-value
PRES	4.0(± 0.85)	3.84(± 1.12)	0.414
SP	3.66(± 0.77)	3.51(± 0.71)	0.88
INV	3.41(± 0.66)	2.99(± 0.7)	0.013*
REAL	2.45(± 0.7)	2.31(± 0.5)	0.19

4.1.2. VR task

A one-way ANOVA analysis of the searching task results showed no impact of the experimental conditions on participants' performances ($F(1, 16) = 0$, $p = 1$, $\eta^2 = 0$).



(a) Deviant waveform



(b) Deviant-standard difference waveform

Figure 4: Grand-average waveform at electrode Cz across conditions for the deviant stimulus (a) and the difference between deviant and standard stimulus (b), with green bar indicating significant differences and standard deviation across the means of the participants.

4.2. Neurophysiological analysis

As detailed in Section 3.4.2, we analyzed the EEG data, first by validating the neurophysiological recordings, then by analyzing the global differences between conditions, in terms of spatial, temporal and ERPs' amplitudes differences.

General waveform We first checked the participants' responses to the oddball paradigm. Figure 3 depict the grand-averaged reaction to the standard and deviant stimuli across conditions on electrode Cz. The differences in waveform (mostly around 300 ms), confirm the difference in perception between these two stimuli. See Figure 8 (Suppl. Mat.) for electrode Fz and Pz.

ERP analysis In order to observe the impact of the experimental protocol, we first check the temporal differences in the data. The grand average ERPs elicited by the deviant oddball stimulus for the two experimental conditions on electrode Cz are shown in Figure 4a. The highlighted areas indicate a significant difference for two ERPs between the two conditions.

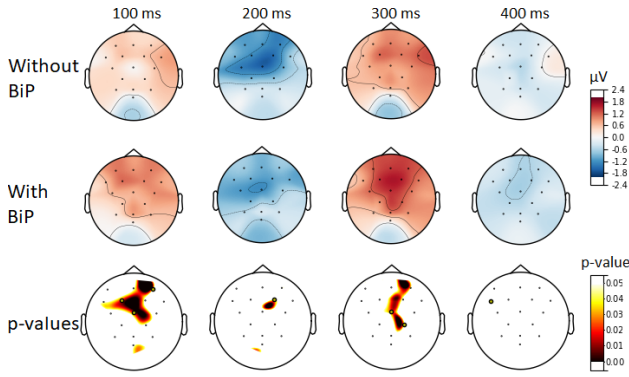


Figure 5: Grand-averaged topography elicited by deviant stimulus over time in `WITHOUT_BiP` and `WITH_BiP` conditions and topography of significant differences between them.

The first one is the P100, recorded around 100 ms, for which the paired t-test showed a significant difference from 100 to 130 ms.

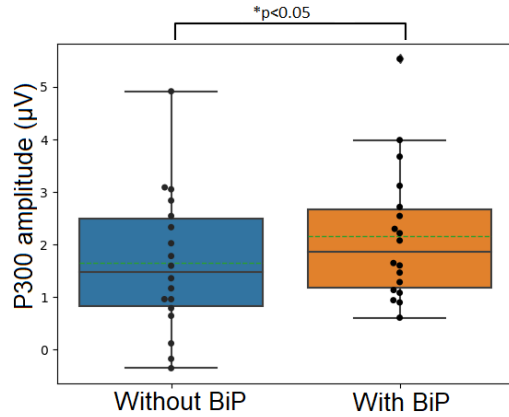
The second is the P300, recorded around 300 ms, for which the paired t-test showed a significant difference from 290 to 315 ms.

This analysis showed no significant difference in the MMN time frame (100-250ms[44]) in the deviant-standard waveform (Figure 4b).

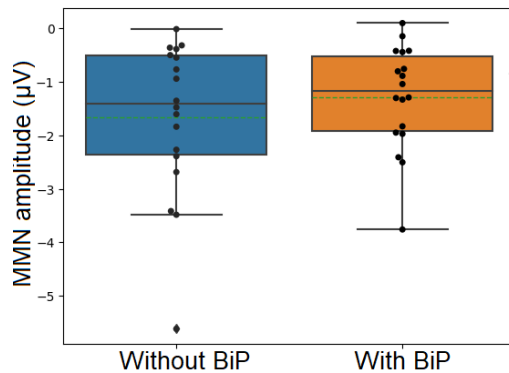
Second, we investigated the spatial origins of these differences. Figure 5 depicts the topographic map of these reactions, along with the topographic representations of significant differences between conditions. We observe an important increase in activity along the fronto-parietal axis for the condition `WITH_BiP` at 100 and 300 ms. With paired t-test analysis, we observed the statistical significance of these differences, revealing a significant effect over centro-frontal areas (Cz and FC1) at 100 ms, and over centro-parietal areas (Cz and CP2) at 300 ms. The localization of the P300 ERP, over frontal to parietal areas is in coherence with the literature, as the P300 scalp distribution changes over the midline electrodes (Fz, Cz, Pz), which typically increases in magnitude from the frontal to parietal electrode sites [23].

Finally, to quantify differences between conditions, we computed the average P300 amplitude in both conditions for each participant. Figure 6a reports the distribution of those amplitudes, showing higher P300 amplitudes in condition `WITHOUT_BiP`. Statistical analysis using repeated-measure ANOVA revealed a significant effect of presence on P300 amplitudes ($F(1, 17) = 5.19$, $p = 0.035$, $\eta^2 = 0.039$). However, no significant difference has been found on the MMN (Figure 6b).

Additionally, 14 participants out of 18 presented a higher P300 in the `WITH_BiP` condition than in the



(a) P300 amplitudes



(b) MMN amplitudes

Figure 6: ERP amplitude recordings of P300 (a) and MMN (b) for `WITHOUT_BiP` and `WITH_BiP` conditions at electrode Cz, with median values represented as solid lines and mean values as dotted lines. The diamond represents an outlier.

`WITHOUT_BiP` condition. On electrodes Cz and Fz, we observe a similar trend (P300 being higher in the `WITH_BiP` condition), although the difference is not significant (see Figure 8, Suppl. Mat.).

4.3. Correlation between self-reported and neurophysiological measurements of presence

Using this P300 measurement, we investigated the relationship between P300 amplitude and participants' questionnaire responses, as stated in Section 3.4.3. Figure 7 illustrates the link between the questionnaire's significant Involvement factor and P300 amplitude, along with a linear regression on these two dimensions for both experimental conditions combined. A significant negative correlation was observed between the two variables through Pearson's correlation coefficient ($r = -0.46$, $p < 0.01$), indicating that higher P300 amplitudes elicited by real-world stimuli

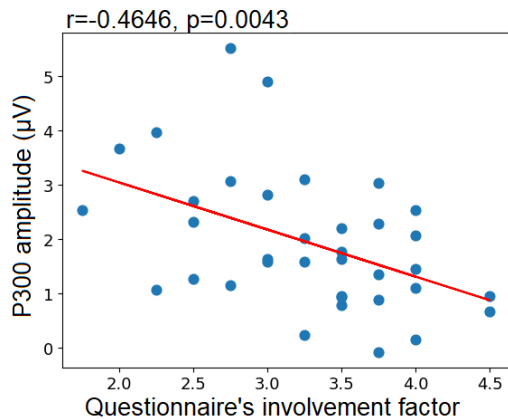


Figure 7: Correlation of subjective response with P300 amplitude. The responses to the Involvement factor for WITHOUT_BiP and WITH_BiP conditions are plotted against the corresponding average P300 amplitude for each subject. The solid red line represents a fitted line by linear regression.

were associated with lower involvement and attention dedicated toward the virtual world. When computing this link in Pz and Fz, we observe a similar significant negative correlation (see Figure 8, Suppl. Mat.).

4.4. Single trial classification

In order to evaluate the feasibility of a real-time classification of presence condition, we applied a single trial classification algorithm on WITHOUT_BiP and WITH_BiP conditions, aiming at determining from which experimental conditions a reaction to a deviant stimulus is coming. Table 2 reports the accuracy, sensitivity (TPR) and specificity (TNR) of the classification for each participant with mean and standard deviation indicated. The average accuracy obtained is 79.5 %, with a chance level determined at 62 % [47], the classification being above chance level for 14 participants out of 18, indicated with a '*' on Table 2.

5. Discussion

In this study, we designed and conducted an experiment to measure through EEG analysis the feeling of presence of participants performing a task in VR. Presence was assessed by measuring the ERP response to an auditory oddball paradigm conducted in the real environment. Our experimental design aimed at generating two virtual experiences which generated distinguishable levels of presence. By artificially modulating the level of presence we hypothesized that the P300 ERP will have higher amplitude in the lower presence condition. In order to generate distinguishable levels of presence,

Table 2: Riemannian geometry-based single-trial classification results between the WITHOUT_BiP and WITH_BiP conditions for accuracy, sensitivity (TPR) and specificity (TNR) averaged on 10 cross-validation repetitions. Standard deviation are indicated in parenthesis. Participants with accuracy above chance level are indicated with '*'.

Participant	Accuracy	TPR	TNR
1*	0.99(±0.01)	0.99(±0.01)	1.0(±0.0)
2*	0.94(±0.02)	0.94(±0.02)	0.93(±0.03)
3*	0.87(±0.01)	0.90(±0.02)	0.83(±0.03)
4	0.46(±0.03)	0.48(±0.04)	0.43(±0.03)
5*	0.92(±0.01)	0.90(±0.01)	0.94(±0.01)
6*	0.99(±0.01)	1.0(±0.0)	0.99(±0.01)
7*	0.65(±0.03)	0.71(±0.05)	0.56(±0.05)
8*	0.95(±0.01)	0.95(±0.01)	0.96(±0.01)
9*	0.88(±0.01)	0.87(±0.02)	0.90(±0.02)
10*	0.84(±0.03)	0.84(±0.03)	0.84(±0.05)
11*	0.68(±0.03)	0.67(±0.03)	0.7(±0.04)
12	0.56(±0.02)	0.58(±0.04)	0.53(±0.05)
13	0.57(±0.03)	0.69(±0.04)	0.41(±0.04)
14*	0.94(±0.03)	0.94(±0.03)	0.94(±0.03)
15*	0.87(±0.03)	0.88(±0.02)	0.85(±0.07)
16*	0.74(±0.02)	0.77(±0.04)	0.70(±0.03)
17*	0.83(±0.05)	0.85(±0.05)	0.81(±0.06)
18	0.55(±0.02)	0.61(±0.05)	0.49(±0.03)
Average*	0.79(±0.16)	0.81(±0.15)	0.77(±0.19)

we introduced “Breaks in Presence” (BiP) during one of the experimental conditions to negatively impact the level of presence experienced by the participants. As a result, we observed in the EEG data, and particularly on the P300 ERP, a significantly higher activity when participants were less present in the VR environment (WITH_BiP condition), than when participants were more present (WITHOUT_BiP condition). Additionally, we used a single-trial classification algorithm using Riemannian geometry able to relatively reliably classify (at 79%) EEG data between the two experimental conditions.

We started our analysis by studying the participant’s responses to the presence questionnaire in order to validate our experimental design and assess the impact of BiP on presence. Participants reported a generally higher presence in the WITHOUT_BiP condition, and specifically a significantly higher involvement toward the virtual environment, than in the WITH_BiP condition. This result confirmed that the use of BiP negatively impacted the feeling of presence. In a precedent study [17], Burns & al. used a video game where they varied the difficulty to produce different levels of presence. Although this method can easily modulate presence, there is a potential risk to have an effect of other factors on participants, such as mental workload. The other precedent studies did not produce any comparisons within participants, they only made par-

ticipants experience a single environment and grouped them depending on their responses to the presence questionnaires. Here, with the use of BiPs, we were able to modulate the level of presence of the participants within the same environment. This protocol reduces the number of factors impacting the participant’s experience, allowing for a more controlled study of presence.

Then, through EEG data analysis, we studied the impact of presence on the reaction to the oddball stimulus. In concordance with previous studies [17, 20, 18, 19], we observed that a lower presence in VR led to a greater EEG response to stimuli displayed in the real environment. Specifically, we have observed this difference in the P300, which is one of the main components studied in the oddball paradigm, as its amplitude is strongly correlated to the difference of attention allocated toward oddball stimuli [23, 24, 22]. P300 recordings on electrode Cz showed significantly higher amplitude in the WITH_BIP condition, revealing that participants were more attentive to the real environment when they were less present in VR. Furthermore, our analysis within participants showed that more than 75 % of the participants (14 out of 18) produced higher P300 in the lower presence condition (WITH_BIP). In addition to electrode Cz, when observing the P300 amplitudes at electrodes Fz and Pz, we notice similar trends, with the P300 amplitude appearing higher under lower presence conditions, although the difference is not statistically significant.

To our knowledge, this is the first study reporting such results, previous studies did not analyze the P300 [17, 18, 19, 20]. We suppose they made this choice as the paradigm didn’t require any active perception of the auditory cues. However, as multiple studies showed that the P300 is relevant in passive oddball paradigms [31, 33], we decided it was relevant to study the P300, and our results show significant differences in P300 amplitudes despite the passive paradigm. Additionally, with our experimental design, we are able to explore the relationship between questionnaire scores and neurophysiological measurements. The analysis showed a negative correlation between participants’ presence scores and the amplitude of the P300 (i.e. the more participants reported being present, the lower the amplitude of the P300 was). In addition to electrode Cz, we found this significant correlation to be robust also on electrode Fz and Pz. This analysis suggests that there is a correlation between the presence experienced by participants, and their attention allocated toward the real environment (observed in the P300 in reaction to the oddball stimulus). It confirms that, while our method measures attention, it also act as a proxy measure for presence.

Although these analysis were reproduced on the

deviant - standard waveform and the MMN, no significant differences were observed. Despite that MMN is rarely affected by attention [48], some studies have reported such an effect. In our case, we suppose that the change in attention levels toward the oddball stimulus wasn’t large enough to impact the MMN amplitude.

Furthermore, the EEG analysis also revealed a significant increase of the P100 amplitude in the lower presence condition (WITH_BIP), for both electrodes Cz and Fz. While this was not an expected result in our study, as we were mainly focused on the P300 and MMN response, a few studies on human attention [49, 50] have reported that attention can impact early ERPs, such as the P100 and N100. Specifically, the P100 is impacted by spatial-selective attention, referring to the ability to focus one’s attention toward a specific location while disregarding others. In our protocol, the oddball stimuli are produced in the real environment and physically located behind the participant. This design likely engages spatial-selective attention within this context. Therefore, we suppose that the observed difference in the P100 amplitude is due to a difference in attention toward the real environment. In the WITHOUT_BIP condition, participants were less attentive and aware of the real environment, thus potentially decreasing the amount of spatial selective attention allocated to it, therefore leading to smaller P100 amplitudes.

Lastly, we investigated the feasibility of assessing presence in real-time. To that extent, we used Riemannian geometry-based single trial classification to discriminate whether the EEG response to the deviant stimuli was from the higher presence condition (WITHOUT_BIP) or from the lower presence condition (WITH_BIP). The results, considering a two-class discrimination, showed an average accuracy of 79% which is coherent with the literature [18], and above chance level, estimated at 62%[47]. However, our two class classification methods rely on the hypothesis that the level of presence is consistent in both conditions, and strictly different. Yet, we cannot confirm this hypothesis, as presence can fluctuate during a condition. Furthermore, the selected channels differs from our ERP analysis: it is likely that the Riemannian classification gathered relevant information outside of Cz channel that has been used for ERP measures. We made the decision to include all channels in this algorithm, as Riemannian algorithms cannot compute correlation matrices over one channel and perform better with additional channels. Although the current study does not achieve ideal classification performance, it still suggests that it could be applied successfully in an online setting, thus providing a real-time presence monitoring with minor participant disturbance. Additionally, we trained one classifier per

participant, which limits the usability of our method in real world applications as a first calibration time would be required for each person before being able to estimate presence level. Future analyses are required to assess if similar results could be obtained using one predefined classifier for all participants. Such analyses could also explore different classifiers as well as spectral, spatial and temporal characteristics that would particularly contribute to the classification accuracy.

Finally, it should be noted that using auditory stimuli can be sometimes detrimental to presence. As reported by one participant, they can be too disturbing to be fully involved in the virtual environment, while others reported that they almost forget their existence. Hence, this paradigm had some impact on the presence experienced by participants. Future works could adapt these stimuli, either by making them more discreet or by using visual or haptic stimuli. Furthermore, individual experience with virtual reality could impact their presence in a virtual environment, as experienced users could be more resilient to Breaks in Presence. Follow-up studies could factor this in.

6. Conclusion

In this paper, we studied a novel method to measure presence based on neurophysiological measurements. This measure of presence is traditionally done via questionnaires, but due to their instability and the inability to use them without highly impacting the feeling of presence, we leveraged electroencephalography (EEG) to assess presence with a reduced impact on participant's experience.

By using an oddball paradigm, we were able to measure the attention allocated to the real environment through the analysis of the P300 response, a potential evoked in response to the oddball stimulus whose magnitude is impacted by the attention allocated toward it. We observed significantly higher amplitudes during the low presence condition, showing that participants were more attentive to the real environment when they were less present in the environment. Due to the negative correlation between presence level and attention level to the real environment, we were able to indirectly measure a user's level of presence.

Future experiments could study different levels of Breaks in Presence to observe a gradual change of P300 amplitudes. They could also use this paradigm while the participants are experiencing VR, to monitor their level of presence in real-time and detect breaks in presence elicited by the environment when a drop in presence occurs. This would allow experimenters to monitor the presence level of participants without the need to interrupt them in their experience of the virtual reality environment.

7. Acknowledgements

This research was partially funded by the French National Research Agency via GENESIS project grant (ANR-21-CHRA-0001-01). We would also to thank all the participants of our experiment for their time and efforts.

8. Supplementary material

Figure 8 & 9 are provided as supplementary material. The VR environment is openly available here: <https://gitlab.inria.fr/esavalle/measuring-presence-in-vr>.

Figure 8 : Duplicated analysis of P300 for the electrode Fz(1), Pz(2). (a) Grand-average waveform of the deviant stimulus across conditions, with green bar indicating significant differences and standard deviation across the means of different participants. (b) P300 amplitudes recordings for the WITHOUT_BIP and WITH_BIP conditions, with median values represented as solid lines and mean values as dotted lines. (c) Correlation of subjective responses with P300 amplitude. The responses to the Involvement factor for WITH_BIP and WITHOUT_BIP conditions are plotted against the corresponding average P300 amplitude for each participant. The solid red line represents a fitted line by linear regression.

Figure 9 : Duplicated analysis of MMN for the electrode Fz(1), Pz(2). (a) Grand-average waveform across conditions for the difference between deviant and standard stimulus, with green bar indicating significant differences and standard deviation across means of different participants (b) MMN amplitudes recordings for the WITHOUT_BIP and WITH_BIP conditions, with median values represented as solid lines and mean values as dotted lines.

9. References

- [1] Mel Slater, Andrea Brogni, and Anthony Steed. Physiological responses to breaks in presence: A pilot study. In *Presence 2003: The 6th annual international workshop on presence*, volume 157. Citeseer Cleveland, OH, 2003.
- [2] Jennifer Brade, Mario Lorenz, Marc Busch, Niels Hammer, Manfred Tscheligi, and Philipp Klimant. Being there again – Presence in real and virtual environments and its relation to usability and user experience using a mobile navigation task. *International Journal of Human-Computer Studies*, 101:76–87, May 2017.
- [3] Richard Skarbez, Frederick P. Brooks, Jr., and Mary C. Whitton. A Survey of Presence and Related Concepts. *ACM Computing Surveys*, 50(6):96:1–96:39, November 2017.
- [4] Takato Mizuho, Takuji Narumi, and Hideaki Kuzuoka. Effects of the Visual Fidelity of Virtual Environments on Presence, Context-dependent Forgetting, and Source-monitoring Error. *IEEE Transactions on Visualization and Computer Graphics*, 29(5):2607–2614, May 2023.

- Conference Name: IEEE Transactions on Visualization and Computer Graphics.
- [5] Richard Skarbez, Frederick P. Brooks, and Mary C. Whitton. Immersion and Coherence: Research Agenda and Early Results. *IEEE Transactions on Visualization and Computer Graphics*, 27(10):3839–3850, October 2021. Conference Name: IEEE Transactions on Visualization and Computer Graphics.
 - [6] Vinicius Souza, Anderson Maciel, Luciana Nedel, and Regis Kopper. Measuring Presence in Virtual Environments: A Survey. *ACM Computing Surveys*, 54(8):163:1–163:37, October 2021.
 - [7] Matthew Price, Natasha Mehta, Erin B. Tone, and Page L. Anderson. Does engagement with exposure yield better outcomes? Components of presence as a predictor of treatment response for virtual reality exposure therapy for social phobia. *Journal of Anxiety Disorders*, 25(6):763–770, August 2011.
 - [8] Stefan Weber, David Weibel, and Fred W Mast. How to get there when you are there already? defining presence in virtual reality and the importance of perceived realism. *Frontiers in psychology*, 12:628298, 2021.
 - [9] Thomas Schubert. The sense of presence in virtual environments: A three-component scale measuring spatial presence, involvement, and realness. *Zeitschrift für Medienpsychologie*, 15:69–71, April 2003.
 - [10] Martin Usoh, Ernest Catena, Sima Arman, and Mel Slater. Using Presence Questionnaires in Reality. *Presence: Teleoperators and Virtual Environments*, 9(5):497–503, October 2000.
 - [11] Mel Slater. How Colorful Was Your Day? Why Questionnaires Cannot Assess Presence in Virtual Environments. *Presence*, 13:484–493, August 2004.
 - [12] Jonathan Freeman, S. E. Avons, Don E. Pearson, and Wijnand A. IJsselstein. Effects of Sensory Information and Prior Experience on Direct Subjective Ratings of Presence. *Presence*, 8(1):1–13, February 1999. Conference Name: Presence.
 - [13] Camille Jeunet, Louis Albert, Ferran Argelaguet, and Anatole Lécuyer. “Do You Feel in Control?”: Towards Novel Approaches to Characterise, Manipulate and Measure the Sense of Agency in Virtual Environments. *IEEE Transactions on Visualization and Computer Graphics*, 24(4):1486–1495, April 2018. Number: 4 Conference Name: IEEE Transactions on Visualization and Computer Graphics.
 - [14] Hakim Si-Mohammed, Catarina Lopes-Dias, Maria Duarte, Ferran Argelaguet, Camille Jeunet, Géry Casiez, Gernot R Müller-Putz, Anatole Lécuyer, and Reinhold Scherer. Detecting System Errors in Virtual Reality Using EEG Through Error-Related Potentials. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pages 653–661, March 2020. ISSN: 2642-5254.
 - [15] Matteo Marucci, Gianluca Di Flumeri, Gianluca Borghini, Nicolina Sciaraffa, Michele Scandola, Enea Francesco Pavone, Fabio Babiloni, Viviana Betti, and Pietro Aricò. The impact of multisensory integration and perceptual load in virtual reality settings on performance, workload and presence. *Scientific Reports*, 11(1):4831, 2021.
 - [16] Christoph Tremmel, Christian Herff, Tetsuya Sato, Krzysztof Rechowicz, Yusuke Yamani, and Dean J. Krusienski. Estimating Cognitive Workload in an Interactive Virtual Reality Environment Using EEG. *Frontiers in Human Neuroscience*, 13, 2019.
 - [17] Christopher G. Burns and Stephen H. Fairclough. Use of auditory event-related potentials to measure immersion during a computer game. *International Journal of Human-Computer Studies*, 73:107–114, January 2015.
 - [18] Silvia Erika Kober and Christa Neuper. Using auditory event-related EEG potentials to assess presence in virtual reality. *International Journal of Human-Computer Studies*, 70(9):577–587, September 2012. Number: 9.
 - [19] Thomas Terkildsen and Guido Makransky. Measuring presence in video games: An investigation of the potential use of physiological measures as indicators of presence. *International Journal of Human-Computer Studies*, 126:64–80, June 2019.
 - [20] Simone Grassini, Karin Laumann, Sebastian Thorp, and Virginia de Martin Topranin. Using electrophysiological measures to evaluate the sense of presence in immersive virtual environments: An event-related potential study. *Brain and Behavior*, 11(8):e2269, 2021. Number: 8 eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1002/brb3.2269>.
 - [21] Mel Slater and Anthony Steed. A Virtual Presence Counter. *Presence*, 9:413–434, October 2000.
 - [22] Dominique Morlet, Perrine Ruby, Nathalie André-Obadia, and Catherine Fischer. The auditory oddball paradigm revised to improve bedside detection of consciousness in behaviorally unresponsive patients. *Psychophysiology*, 54(11):1644–1662, 2017. Number: 11 eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1111/psyp.12954>.
 - [23] John Polich. Updating P300: An Integrative Theory of P3a and P3b. *Clinical neurophysiology : official journal of the International Federation of Clinical Neurophysiology*, 118(10):2128–2148, October 2007.
 - [24] Albert Kok. On the utility of P3 amplitude as a measure of processing capacity. *Psychophysiology*, 38(3):557–577, 2001. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1017/S0048577201990559>.
 - [25] George Al Boustani, Lennart Jakob Konstantin Weiß, Hongwei Li, Svea Marie Meyer, Lukas Hiendlmeier, Philipp Rinklin, Bjoern Menze, Werner Hemmert, and Bernhard Wolfrum. Influence of auditory cues on the neuronal response to naturalistic visual stimuli in a virtual reality setting. *Frontiers in Human Neuroscience*, 16:809293, 2022.
 - [26] John R. Wilson, S. Nichols, and Clovissa Haldane. Presence and Side Effects: Complementary or Contradictory? In *HCI international 1995*, 1997.
 - [27] Silvia Erika Kober, Jürgen Kurzman, and Christa Neuper. Cortical correlate of spatial presence in 2D and 3D interactive virtual reality: An EEG study. *International Journal of Psychophysiology*, 83(3):365–374, March 2012.
 - [28] Françoise Lecaigard, Olivier Bertrand, Gérard Gimenez, Jérémie Mattout, and Anne Caclin. Implicit learning of predictable sound sequences modulates human brain responses at different levels of the auditory hierarchy. *Frontiers in Human Neuroscience*, 9, 2015.
 - [29] J. Peter Rosenfeld, Khavita Bhat, Amy Miltenberger, and Mary Johnson. Event-related potentials in the dual task paradigm: P300 discriminates engaging and non-engaging films when film-viewing is the primary task. *International Journal of Psychophysiology*, 12(3):221–232, May 1992.
 - [30] Daniel Strüber and John Polich. P300 and slow wave from oddball and single-stimulus visual tasks: inter-stimulus interval effects. *International Journal of Psychophysiology*, 45(3):187–196, September 2002.
 - [31] Nikol Figalová, Hans-Joachim Bieg, Julian Elias Reiser, Yuan-Cheng Liu, Martin Baumann, Lewis Chuang, and Olga Pollatos. From Driver to Supervisor: Comparing Cognitive Load and EEG-based Attentional Resource Allocation across Automation Levels. *International Journal of Human-Computer Studies*, 182:103169, February 2024. arXiv:2306.08477 [cs].
 - [32] E. Fucci, O. Abdoun, A. Caclin, A. Francis, J.D. Dunne, M. Ricard, R.J. Davidson, and A. Lutz. Differential effects of non-dual and focused attention meditations on the formation of automatic perceptual habits in expert practitioners. *Neuropsychologia*, 119:92–100, October 2018.

- [33] J. Polich. P300 from a passive auditory paradigm. *Electroencephalography and Clinical Neurophysiology*, 74(4):312–320, 1989.
- [34] Christoph Justen and Cornelia Herbert. The spatio-temporal dynamics of deviance and target detection in the passive and active auditory oddball paradigm: a soreta study. *BMC neuroscience*, 19:1–18, 2018.
- [35] R. Näätänen, T. Kujala, C. Escera, T. Baldeweg, K. Kreegipuu, S. Carlson, and C. Ponton. The mismatch negativity (MMN) – A unique window to disturbed central auditory processing in ageing and different clinical conditions. *Clinical Neurophysiology*, 123(3):424–458, March 2012.
- [36] Mel Slater, R. Lotto, Maria Arnold, and Maria Sanchez-Vives. How we experience immersive virtual environments: The concept of presence and its measurement. *Anuario de Psicología*, 40, September 2009.
- [37] Stephen Palmisano, Robert S. Allison, and Juno Kim. Cybersickness in Head-Mounted Displays Is Caused by Differences in the User’s Virtual and Physical Head Pose. *Frontiers in Virtual Reality*, 1, 2020.
- [38] Mel Slater, Xavi Navarro, Jose Valenzuela, Ramon Oliva, Alejandro Beacco, Jacob Thorn, and Zillah Watson. Virtually Being Lenin Enhances Presence and Engagement in a Scene From the Russian Revolution. *Frontiers in Robotics and AI*, 5, 2018.
- [39] Yann Renard, Fabien Lotte, Guillaume Gibert, Marco Congedo, Emmanuel Maby, Vincent Delannoy, Olivier Bertrand, and Anatole Lécuyer. OpenViBE: An Open-Source Software Platform to Design, Test and Use Brain-Computer Interfaces in Real and Virtual Environments. *Presence Teleoperators & Virtual Environments / Presence Teleoperators and Virtual Environments*, 19, February 2010.
- [40] Alexandre Gramfort, Martin Luessi, Eric Larson, Denis Engemann, Daniel Strohmeier, Christian Brodbeck, Roman Goj, Mainak Jas, Teon Brooks, Lauri Parkkonen, and Matti Hämäläinen. MEG and EEG data analysis with MNE-Python. *Frontiers in Neuroscience*, 7, 2013.
- [41] Pierre Comon. Independent component analysis, A new concept? *Signal Processing*, 36(3):287–314, April 1994.
- [42] Tzyy-Ping Jung, Colin Humphries, Te-Won Lee, Scott Makeig, Martin McKeown, Vicente Iragui, and Terrence J Sejnowski. Extended ica removes artifacts from electroencephalographic recordings. In M. Jordan, M. Kearns, and S. Solla, editors, *Advances in Neural Information Processing Systems*, volume 10. MIT Press, 1997.
- [43] Tzyy-Ping Jung, Scott Makeig, Marissa Westerfield, Jeanne Townsend, Eric Courchesne, and Terrence J Sejnowski. Removal of eye activity artifacts from visual event-related potentials in normal and clinical subjects. *Clinical neurophysiology*, 111(10):1745–1758, 2000.
- [44] Risto Näätänen, Satu Pakarinen, Teemu Rinne, and Rika Takegata. The mismatch negativity (MMN): towards the optimal paradigm. *Clinical Neurophysiology*, 115(1):140–144, January 2004.
- [45] Alexandre Barachant. MEG decoding using Riemannian geometry and unsupervised classification. *Grenoble University: Grenoble, France*, 2014. Publisher: Citeseer.
- [46] Bertrand Rivet, Antoine Souloumiac, Virginie Attina, and Guillaume Gibert. xDAWN algorithm to enhance evoked potentials: application to brain-computer interface. *IEEE Transactions on Biomedical Engineering*, 56(8):2035, 2009. Publisher: Institute of Electrical and Electronics Engineers (IEEE).
- [47] Gernot Müller-Putz, Reinhold Scherer, Clemens Brunner, Robert Leeb, and Gert Pfurtscheller. Better than Random? A closer look on BCI results. *International Journal of Bioelectromagnetism*, 10:52–55, January 2008.
- [48] Marta I. Garrido, James M. Kilner, Klaas E. Stephan, and Karl J. Friston. The mismatch negativity: A review of underlying mechanisms. *Clinical Neurophysiology*, 120(3):453–463, March 2009.
- [49] Christoph S Herrmann and Robert T Knight. Mechanisms of human attention: event-related potentials and oscillations. *Neuroscience & Biobehavioral Reviews*, 25(6):465–476, August 2001.
- [50] George R. Mangun and Steven A. Hillyard. Modulations of sensory-evoked brain potentials indicate changes in perceptual processing during visual-spatial priming. *Journal of Experimental Psychology: Human Perception and Performance*, 17(4):1057–1074, 1991. Place: US Publisher: American Psychological Association.