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Abstract:

This study aimed to compare a neuropsychological test tapping into executive control function, the Wisconsin Card Sorting Test (WCST), performed in either traditional paper-and-pencil (PP) or virtual reality (VR) modality, and to determine the role of human factors (*i.e.* sense of presence, cybersickness, field (in)dependence and video game experience) as contributors to performance and perceived mental effort. Indeed, if virtual assessment might bring the ecological dimension to controlled laboratory research, it is often suggested that human factors might bias performance. WCST performance and its associated perceived mental effort were compared between the two modalities (N = 107). In the VR modality (N = 52), a correlation matrix was conducted as well as a cluster analysis in order to build two experimental groups, or profiles, based on their subjective experience of VR. WCST performance and perceived mental effort were then compared between these two groups while controlling for age and education. Results outlined a similar WCST performance and perceived mental effort between the PP and VR modalities. However, when comparing the two VR groups, results suggest that an unfavorable profile for VR, *i.e.* less sense of presence, more cybersickness, more visual field dependence and less video game experience, is associated with greater perceived mental effort. These experimental findings enable outlining a new conceptual and methodological framework for the assessment of executive control task performance in VR. Results could help users to take human factors into consideration in order to fully exploit or predict the benefits of this tool.

Keywords: Sense of presence; Cybersickness; Field dependence-independence; Video game experience; Executive control of attention.

Introduction

Virtual reality (VR) has emerged over the last decades as a new technology in scientific research, and particularly in education (Chen 2009; Christou 2010; Kamińska et al. 2019; Leung et al. 2018; Pantelidis 2009), health (Freeman et al. 2017; Gregg and Tarrier 2007; Riva et al. 2019; Scozzari and Gamberini 2011) and research (Bohil et al. 2011; Canning et al. 2020; de la Rosa and Breidt 2018; Pan and Hamilton 2018; Parsons et al. 2017). The possibilities it offers to simulate complex situations allow researchers to study human behavior in a controlled and customized environment, which allows assessing conditions which are both ecological and controlled for the laboratory evaluation of ecological situations (Coleman et al. 2019; Parsons 2015). Minderer et al. (2016) said that it allows the junction between of the "best of two worlds”: controlled laboratory experiments with more ecological validity. Among many examples of applications, VR allows an ecological assessment of spatial cognition in the diagnosis of neurodegenerative diseases through the exploration of a “real” but virtual town (Cogné et al. 2017). However, today's VR is not completely transparent, and if we can, to a certain degree, speak about an "illusion of non-mediation" (Lombard and Ditton 1997), it is clearly not total, in particular with regard to the sensory integration. Indeed, VR consists in applying a sensory-motor artificial filter called “immersion” which allows the researcher to observe a behavioral response to the desired stimuli. This sensory-motor filter is superimposed on the information from the physical world and does not completely replace it. It is within this discrepancy that the problem of the human factors – performance relationship in VR arises: The psychophysiological response of an individual to this discrepancy varies widely between individuals (Maneuvrier et al. 2021; Weech et al. 2019), which might differently impact task performance and user’s attention level (Maneuvrier et al. 2020), leading to biased assessments.

Subjective experience of VR

One of the major psychophysiological aspects discussed in the field of VR as potentially impacting performance is the sense of presence, the “sense of being there” (Heeter 1992; Sheridan 1992, 1996, 2016). While its understanding and experimentation are instinctive, its definition is more complicated. Its definition emphasizes either the “media” presence, which occurs when “a person failed to perceive or acknowledge the existence of a medium” (Lombard and Ditton 1997), or the “inner” presence, defined as a “broad psychological phenomenon not necessarily linked to the experience of a medium” (Coelho et al. 2009; Riva et al. 2011, 2015). In these views, the phenomenon is considered a deep evolutionary neurological cognitive process very close to the concept of consciousness and attention (Coelho et al. 2009; Riva 2006; Riva and Waterworth 2003). Beyond these theoretical discrepancies, the knowledge concerning its impact on performance remains limited (Barfield et al. 1995). Several studies suggest that the sense of presence (i) is intrinsically related to user’s attention level (Bystrom et al. 1999; Draper et al. 1998; Draper and Blair 1996) and (ii) might enhance task performance in a VR environment (Cooper et al. 2018; Maneuvrier et al. 2020; Slater et al. 1996; Stanney et al. 2002; Stevens and Kincaid 2015; Witmer and Singer 1998). However, it has to be noted that this effect is not systematically found in the literature (Nash et al. 2000; Persky et al. 2009; Singer et al. 1995; Welch 1999), which might be explained by (i) the very different forms that performance can take (Maneuvrier et al. 2020; Nash et al. 2000), and (ii) the dynamic and complex nature of the sense of presence, which depends on the interaction between extrinsic (immersion) and intrinsic (human) factors. System factors correspond to the characteristics of the immersive system (for a meta-analysis on extrinsic factors affecting the sense of presence, see Cummings and Bailenson (2016)), while human factors constitute other psychophysiological aspects that will be associated with the sense of presence, the most famous one being cybersickness. Indeed, the most prevalent negative effects of VR are often grouped under the term “cybersickness” which can be considered as the negative counterpart of the sense of presence. It is described as a set of symptoms similar to those of motion sickness and caused by exposure to VR (Rebenitsch and Owen 2016). Motion sickness symptoms are often suggested as the manifestation of evolutionary processes with the function to expel toxic ingested molecule detected by a mismatch between the different sensory systems (Reason and Brand 1975; Treisman 1977). Cybersickness is sometimes called “visually induced motion sickness” when they appear in VR since they are mostly triggered by visual mismatch (Bos et al. 2008; Stanney et al. 1997). This term, cybersickness, encompasses other negative aspects, notably visual fatigue, even though it is not triggered by the sensory mismatch directly but rather by the vergenceaccommodation conflict induced by stereoscopy (Rebenitsch and Owen 2021; Souchet et al. 2021; Ukai and Howarth 2008). Regarding the impact of these negative effects within the psychophysiology of VR, a recent literature review outlined that cybersickness symptoms are negatively correlated with the sense of presence (Weech et al. 2019). This is of fundamental interest since it has been shown that motion sickness symptoms are associated with reduced cognitive performance (Gresty et al. 2008; Gresty and Golding 2009; Kennedy et al. 1993; Maneuvrier et al. 2020; Nesbitt et al. 2017; Stanney et al. 2002; Stróżak et al. 2018; Szpak et al. 2019) and greater perceived mental effort (Loup and LoupEscande, 2019; Park 2020). It has to be noted that this negative effect of cybersickness on cognitive performance has been questioned by Varmaghani et al. (2021), outlining the potentiality of a threshold effect (Maneuvrier et al. 2020; Varmaghani et al. 2021). Beyond pure visual stress leading to cognitive fatigue (Lambooij et al. 2009; Sheppard and Wolffsohn 2018; Souchet et al. 2021), several mutually inclusive interpretations are possible to explain that VR costs more mental effort: (i) the participant's endogenous attention is drawn away from the task to proprioception and symptoms’ awareness, (ii) the nervous system tries to adapt to the sensory mismatch by down-weighting and inhibiting incongruent visual information, and iii) the nervous system tries to adapt and compensate for its postural instability caused by the sensory mismatch in order to improve motor control and balance (Arcioni et al. 2019; Chardonnet et al. 2017; Guerraz et al. 2001; Hakkinen et al. 2002; Mahboobin et al. 2005; Palmisano et al. 2018; Stoffregen and Smart 1998). For all of these reasons, the opposite pairing of the sense presence and cybersickness can be considered at the core of the subjective experience of VR (Maneuvrier et al. 2021), which can be a concern for VR performance assessments because its sensitivity varies widely from one individual to another, notably due differences in their use of visual information and their experience of video games (cf. infra).

Cognitive profile of VR

Visual field dependence ‑ independence (FDI) is defined as the degree to which a person’s perception is affected by the context and the strength of the surrounding visual field (Witkin 1949; Witkin et al. 1954, 1962, 1977). Visual FDI is a continuum of cognitive and perceptive style: visual fielddependent subjects use predominantly visual cues and holistic strategies, while visual field-independent subjects use predominantly non-visual cues (vestibular, proprioceptive) and analytic strategies. For what concerns us, visual FDI, sometimes called sensitivity to visual cues is positively correlated with motion sickness susceptibility (Kennedy 1975) and cybersickness symptoms (Cian et al. 2011; Maneuvrier et al. 2021; Stanney et al. 2020), which is interpreted as the result of a predominant use of incongruent visual cues in VR, and/or a less adapted/flexible integration of multiple sensory cues (Fulvio et al. 2021; Maneuvrier et al. 2021; Weech et al. 2020a, b). In visual field-dependent subjects, the predominant use of visual cues, often problematic in VR and leading to cybersickness symptoms, requires them to down-weight visual information (Keshavarz et al. 2017; Mahboobin et al. 2005; Maneuvrier et al. 2021; Scotto Di Cesare et al. 2015; Weech et al. 2020a, b). In addition, visual field independence has been found to be positively associated with the sense of presence (Hecht and Reiner 2007; Maneuvrier et al. 2021), which has been suggested to result from better inhibition and spatial abilities and greater capacity of using internal cues to overcome visual flaws in the virtual environment. For all these reasons, and because visual cues usually are i) the most prevalent sensory modality in a virtual environment, ii) the most prevalent sensory modality among humans, or so it seems (Hutmacher 2019), and (iii) the cause of cybersickness, it appears that visual FDI might be crucial for the understanding of the sensory reweighting mechanism and thus the psychophysiological adaptation in VR (Cian et al. 2011; Mahboobin et al. 2005; Scotto Di Cesare et al. 2015). For example, Weech et al. (2020a, b) found an association between down-weighting of visual information when exposed to visual oscillations and lower scores of disorientation and oculomotor symptoms of cybersickness during VR immersion. In the same vein, Maneuvrier et al. (2021) found that individuals who were least able to adapt to VR (more cybersickness, less sense of presence) were more likely to reduce their visual FDI (i.e., down-weight visual cues) during VR immersion. Another factor often considered as influencing the subjective experience of VR is the individual’s video game experience. Indeed, video game experience seems to improve the susceptibility/sensitivity to the sense of presence in VR (Gamito et al. 2008, 2010; Knight and Arns 2006; Lachlan and Krcmar 2011; Maneuvrier et al. 2020; Stanney et al. 2003; Weech et al. 2020a, b), even though this effect is not systematic (Alsina-Jurnet and Gutiérrez-Maldonado 2010; Ling et al. 2013). It is possible that video game players are more prone to the sense of presence because of the many ergonomic, motor and perceptual similarities between video games and VR, resulting in reduced allocation of attentional resources to the interface: by better recognizing cognitive schemes and affordances in the VR environment, video game players have more attentional resources available to focus on the task at hand. In addition, many video games rely on spatial cognitive processes, which are sometimes linked to the sense of presence (sometimes called "spatial presence"). However, it is difficult to infer causality: It is possible that playing video games leads to greater sense of presence, just as it is possible that individuals who are more prone to the sense of presence are more attracted to video games. Furthermore, video game experience also seems to reduce the susceptibility of cybersickness (De Leo et al. 2014; Maneuvrier et al. 2020). One interpretation being that playing video games provokes a habituation to the sensory mismatch: video game players being more used than nonplayers to incongruent visual flow as the latter is very common in video games, and notably first-person video games (Howarth and Hodder 2008). Finally, it should be noted that this list of interrelated human factors influencing the experience in VR is obviously not exhaustive, and we only cite (and study) here the main ones mentioned in the literature, as other factors have been mentioned: age (Paillard et al. 2013), emotions (AymerichFranch 2010; Riva et al. 2007), personality (Dewez et al. 2019; Kober and Neuper 2013), gender and/or sex (Clemes and Howarth 2005; Felnhofer et al. 2012; Gamito et al. 2008; Lachlan and Krcmar 2011) and obviously the quality and quantity of the available attentional resource pools which are direct moderators of cognitive performance and perceived mental effort (Bystrom et al. 1999; Draper et al. 1998; Draper and Blair 1996).

Research question

From then, it is possible to apprehend the above-mentioned human factors as a broad "cognitive profile" favorable or unfavorable to VR (Maneuvrier et al. 2021). This cognitive profile will be influenced by contextual factors (fatigue, hunger, volition, etc.) and system factors (immersion) to build the individual's psychophysiological subjective experience of VR described previously. For our purposes here, it is this subjective experience of VR that could, during the interaction with the VR environment, potentially bias the measurements made: Some individuals would thus be favored by a good psychophysiological adaptation. Indeed, if the use of VR as a tool for assessment decreases or increases performance depending on some individual traits, it creates a systematic bias inherent to the medium that must be quantified and neutralized to make VR a rigorously scientific tool. The present study, as many in virtuo experiments performed in the last decades, aims to help the emergence of a new conceptual and methodological framework for the assessment of task performance in immersive virtual environments (North and North 2016). Accordingly, our first objective was to compare cognitive performance and its associated perceived mental effort during a standard neuropsychological test, the Wisconsin Card Sorting Test (WCST), performed either in traditional paper-and-pencil (PP) or VR modality. Our second objective was to determine the impact and origin of multiple human factors: sense of presence, cybersickness, visual FDI and video game experience as contributors to executive control task performance (WCST) and its associated perceived mental effort in the VR modality. Considering all this, our first hypothesis is that there will be no difference in executive control task performance nor perceived mental effort between the two modalities (PP vs. VR). Our second hypothesis is that, in the VR modality, a better cognitive performance and a lower perceived mental effort will be associated with a favorable cognitive profile to VR and a good psychophysiological subjective experience of VR (i.e., more sense of presence, less cybersickness, less visual FDI and more video game experience).

Material and methods

109 young adults were locally recruited at the university campus by either public (posters in the university) or social media announcements. Exclusion criteria included: (i) being under 18 or over 35 years of age, (ii) current presence of neurological or psychiatric disorders impacting perception, (iii) visual impairments that do not allow stereoscopic vision, and (iv) motor impairments that do not allow the use of hand controllers. This research complied with the tenets of the Declaration of Helsinki and was approved by the CLERS (“Comité Local d’ Éthique de la Recherche en Santé” /Local Health Research Ethics Committee, reference: 042020FLE-MAN).

Informed consent was obtained from each participant. The informed consent form contained information about the voluntary nature of the study and the right to withdraw from participating at any time. The participants were asked to complete and sign the informed consent form to acknowledge their willingness to volunteer. Even though they were informed that they could stop the experiment at any time, none of them chose to. Two participants were removed from the study as they were considered outliers on their cybersickness scores (over 3 standard deviations). The remaining participants were divided into two groups for which sex parity was pseudo-randomly controlled: a VR group of 27 women (23.6 ± 2.7 years old) and 25 men (25.1± 3.4 years old) and a PP group of 28 women (24.5 ± 3.1 years old) and 27 men (24.7 ± 3.5). A within-subjects (repeated-measures) design was not used to avoid any learning effect from one modality to another.

WCST in PP and VR modalities

The traditional PP modality of the WCST (Berg 1948) is considered as a global measure of executive control, tapping into inhibition, perseverance, abstract thinking and set-shifting (Kopp et al. 2019). This test allows neuropsychologists to reveal frontal lobe dysfunctions or neurodegenerative diseases (Milner 1963; Lange et al. 2018). Concretely, four "reference" cards are presented to the participant. Each card corresponds to one possible combination of three features: one color (red, blue, green, yellow), one shape (triangle, circle, square) and one number (1, 2, 3, 4). A fifth "stimulus" card is then presented, which also includes a combination of these three same features. The participant is asked to match the stimulus card with one of the reference cards. After an answer has been given, without any clues regarding the rule (i.e., sorting category), the participant receives positive ("yes") or negative ("no") feedback from the experimenter. When the participant correctly answers 10 times in a row, the rule is considered found. So, the experimenter moves on to the next rule without warning the subject as to how the stimulus and reference cards are to be matched and without changing the reference cards. The test ends when the 6 rules (i.e., sorting by color, shape, number, color, shape, number) are found or when the deck of 128 cards is used (i.e., 128 trials). WCST performance was considered as the number of trials needed to find the 6 rules. For clarity issues, this error score was inverted: A higher score indicates a better performance. An automatic VR version of the WCST on the HTCVive® head-mounted display (1080 × 1200 pixels per eye, 90 Hz display refresh rate, 110 degrees horizontal and 90-degree vertical field of view) was developed in order to compare the WCST performance between PP and VR modalities. Designed by the authors for the present study, the virtual WCST has been implemented in an American Far West environment in order to use a background culturally known without going for a hyper-realistic style (Fig. 1). The virtual environment was made using Unity3D® and the C# programming language. It ran on a computer using a NVIDIA® GTX-1080 graphic card, 16 GB of RAM and an Intel Core i5® which ensured a consistent frame rate (i.e., 90 frames per second). In the same way as in the PP modality, the participant was seated on a chair, but virtually seated on a moving cart navigating through an audio-visual environment. The use of a visual flow was justified by two aspects: first, and mainly, in order to induce behavioral differences related to visual FDI, notably by triggering sensory reweighting mechanisms. In addition, displacement allowed the participant to feel like they were moving forward in the virtual environment and exploring a larger portion of it, which seemed favorable to the emergence of the sense of presence studied here. The four reference cards were presented on the corners of a cart moving in front of the participant, and the fifth stimulus card appeared in the middle of the cart equidistant from the reference cards (instead of ‘GO’ in Fig. 1). The participants performed the test by manipulating a virtual laser via a fully tracked controller in order to match the stimulus card with one of the reference cards. Performance feedback was delivered by a colored visual cue (red to failure or green to success) associated with a brief acoustic cue to preserve the sense of presence. Since the test was virtual and automatic, the experimenter was almost fully absent from the procedure, as the rules were explained in the virtual environment. Performance score was computed in the same way as in the PP modality. Both modalities of WCST followed the same original procedure and were validated by a professional clinical neuropsychologist.

Figure 1. Screenshot of the Wisconsin Card Sorting Test in the VR modality on the HTC Vive Pro head-mounted display.

Experimental procedure

Once the WCST was completed, participants from the VR group had to respond to the French validated Questionnaire of Presence (Robillard et al. 2002; Witmer and Singer 1998), except for haptic-related questions as the environment had no haptic feedback and to the French validated Simulator Sickness Questionnaire (Bouchard et al. 2007; Kennedy et al. 1993). To prevent a suggestive effect of the enunciation of cybersickness symptoms, only the post-test questions of the Simulator Sickness Questionnaire were used. The perceived mental effort associated with WCST performance was evaluated through a 7-point Likert scale from 1 “Completely disagree” to 7 “Completely agree” (“This task required a high degree of mental effort”). The participant then had to answer a one-item question to constitute the video game experience variable (“How often do you play video games?”), using a 7-point Likert scale from 1 (“never”) to 7 (“every day”). Effects of age and education were considered as potential important confounders for WCST performance and perceived mental effort. Sex was measured to ensure parity in the sample. Lastly, visual FDI was evaluated using a virtual Rod-and-Frame Test (RFT; RVR software by Virtualis®). Positioned in an upright seated position and equipped with a VR headset, participants had to align, via a joystick, a rod initially tilted 27 degrees to earthly vertical (0 degree), in a fixed frame laterally tilted 18 degrees (Cian et al. 2011; Keshavarz et al. 2017). Sixteen trials were performed from balanced order combinations of two right and left rod tilts and two right and left frame tilts. For each trial, the absolute error (in degree) relative to the earth vertical was recorded. The degree of field (in)dependence was quantified using the mean absolute error (Bagust et al. 2013; Hayes and Venables 1972; Keshavarz et al. 2017). The higher the mean absolute error, the more the subjective vertical is influenced by the tilted frame, and thus the more the subject is visual field dependent.

Statistical analysis

All statistical analyses were performed using a mix of R version 1.2.5001-3 and JASP version 0.14.3. The McDonald's Omega Coefficient (ω) was calculated in order to check the reliability of the two VR variables built using questionnaires (sense of presence, cybersickness). In addition, and for VR methodological transparency, the VR questionnaire variables were compared to their validated norms using a one-sample t-test. Pearson's correlation was used to test the association between WCST performance and perceived mental effort. On the whole sample (N = 107), two one-way ANCOVA (independent measures) were conducted to determine the effect of modality (VR vs. PP) on WCST performance and perceived mental effort, respectively, while controlling for age and education as well as visual FDI and video game experience. Within the VR modality (N = 52), a correlation matrix was conducted in order to apprehend the global relationships between the different VR variables (i.e., sense of presence, cybersickness, video game experience, visual FDI) and the two dependent variables (i.e., WCST performance and perceived mental effort) using Pearson's r. Because our a priori predictions were directional, one-tailed tests were used for correlation analyses. A k-means clustering unsupervised machine learning algorithm (25 iterations maximum, 25 random sets, Hartigan–Wong algorithm) was conducted using sense of presence, cybersickness, video game experience and visual FDI as variables in order to 1) consider the human factors as a global intertwined set of variables and 2) build experimental groups based on their subjective experience of VR. The number of clusters k was set to 2 to compare individuals with a favorable cognitive profile and a good subjective experience of VR (VRE +) and individuals with an unfavorable cognitive profile and a poor experience of VR (VRE−). Then, two one-way ANCOVA (independent measures) were conducted to determine the effect of subjective experience of VR (VRE + vs. VRE-) on WCST performance and perceived mental effort, respectively, while controlling for age and education. For each ANCOVA analysis, homogeneity was tested using the Levene's test, standardized residuals were checked using the Q – Q plot, and post hoc Holm's corrections and Tukey's tests were used to investigate further the potential differences. Quantitative data were expressed as the mean ± standard deviations. The significance threshold was set at 0.05. Effect sizes were reported through the partial etasquared (η 2) for ANCOVA, the r coefficient for correlations, and the Cohen's d for t-tests. Confidence intervals were set at 95% and systematically reported.

Results

With a mean of 106.05 ± 9.84 (without haptic and audio items) compared to that of 91.96 ± 18.99 from the original data from the French validated Questionnaire of Presence (Robillard et al. 2002; Witmer and Singer 1998), our participants had a greater sense of presence: $t_{51} = 10.58$, $p < 0.001$, Cohen's d = 1.46, 95% CI [1.07, 1.85]. The reliability analysis reported a McDonald's omega coefficient (ω) of 0.81, 95% CI [0.36, 0.88] for the French Presence Questionnaire scores. With a mean of 2.86 ± 2.35 compared to that of 7.12 ± 6.04 of the original data from the French validated SSQ, our participants experienced a higher level of cybersickness: $t_{51} = -13.04$, $p < 0.001$, Cohen's d = −1.8, 95% CI [−2.24, −1.36]. The reliability analysis reported a McDonald's omega coefficient (ω) of 0.7, 95% CI [0.53, 0.81] for SSQ scores. The perceived mental effort score (2.52 ± 1.5) was positively correlated with WCST performance (99.21 ± 20.88): n = 107, r = 0.765, $p < 0.001$, 95% CI [0.67, 0.83].

Between-group comparisons: PP *vs.* VR

No significant effect of the modality (PP vs. VR) was found on neither WCST performance nor perceived mental effort after controlling for age and education. However, education significantly predicted WCST performance $F_{1,101} = 11.4$, $p < 0.001$.

Intra-VR modality analyses

The heatmap of the correlation matrix (Pearson ’ s r) on the four human factors (sense of presence, cybersickness, visual FDI, video game experience) and the two dependent variables (WCST performance and perceived mental effort) is presented in Fig. 2. The descriptive statistics of the two groups extracted from the k-means clustering analysis using sense of presence, cybersickness, visual FDI and video game experience dimensions as variables are reported in Table 1 ($N = 52$, $R2 = 0.34$, $AIC = 150$, $BIC = 165.8$, silhouette = 0.29, Fig. 3). The first cluster was designated as the VRE- cluster (i.e., poor subjective experience of VR), and the second cluster as the VRE + cluster (i.e., good subjective experience of VR).

		VRE+	VRE-
Sense of presence	Mean	125.8	118.76
	SD	9.89	12.94
Cybersickness	Mean	1.61	4.11
	SD	1.6	2.33
FDI	Mean	4.03	8
	SD	1.44	2.72
Video game experience	Mean	5.3	1.63
	SD	2.27	1.01

Table 1. Descriptive statistics (mean ± standard deviation) of the human factors in the VRE + and VRE− clusters.

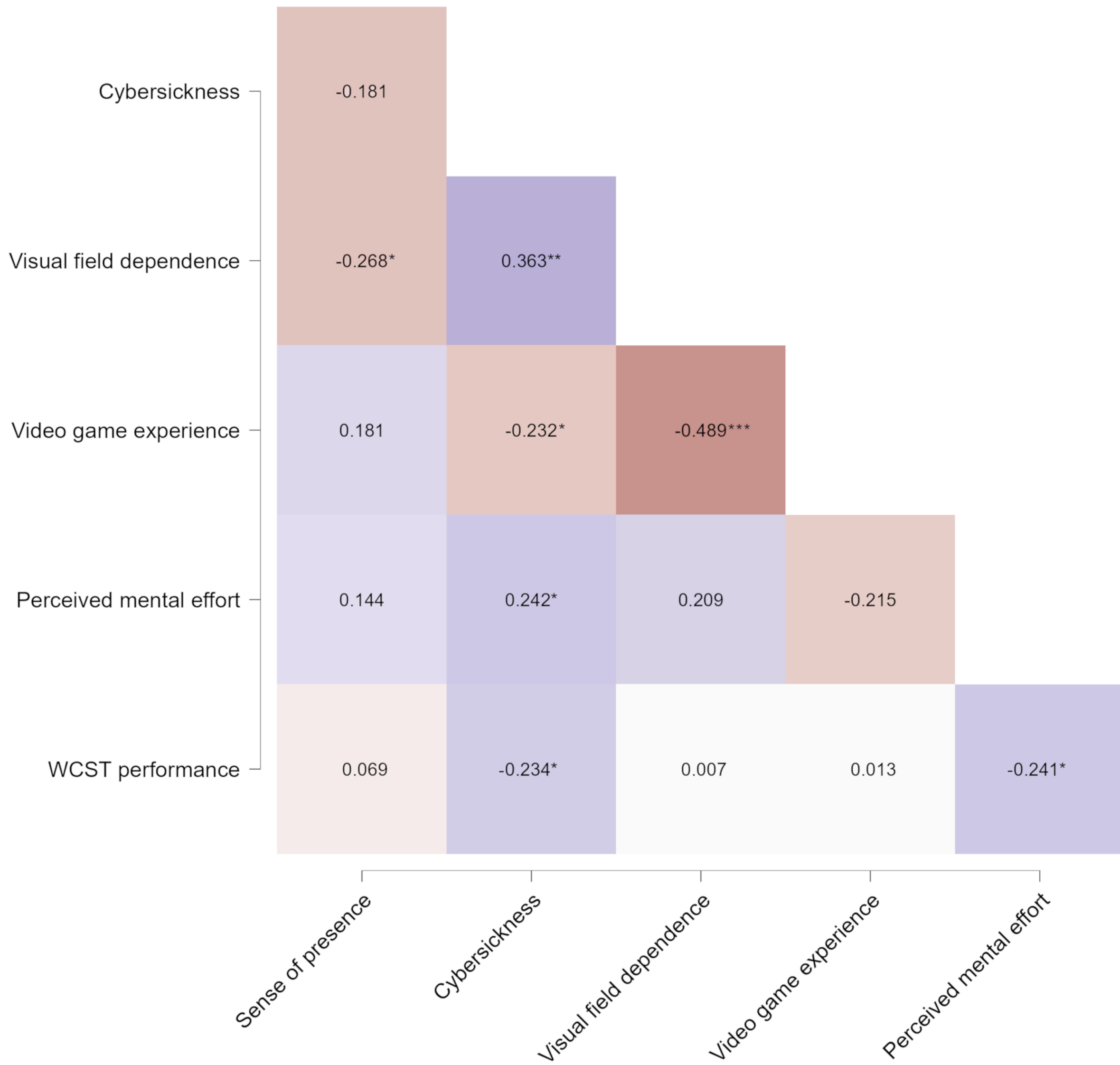

Figure 2. Heatmap (N = 52) of the correlation matrix (Pearson's r) on the four human factors (sense of presence, cybersickness, visual FDI, video game experience) and the two dependent variables (WCST performance and perceived mental effort). Significance levels: *p < .05, **p < .01 ***p < .001

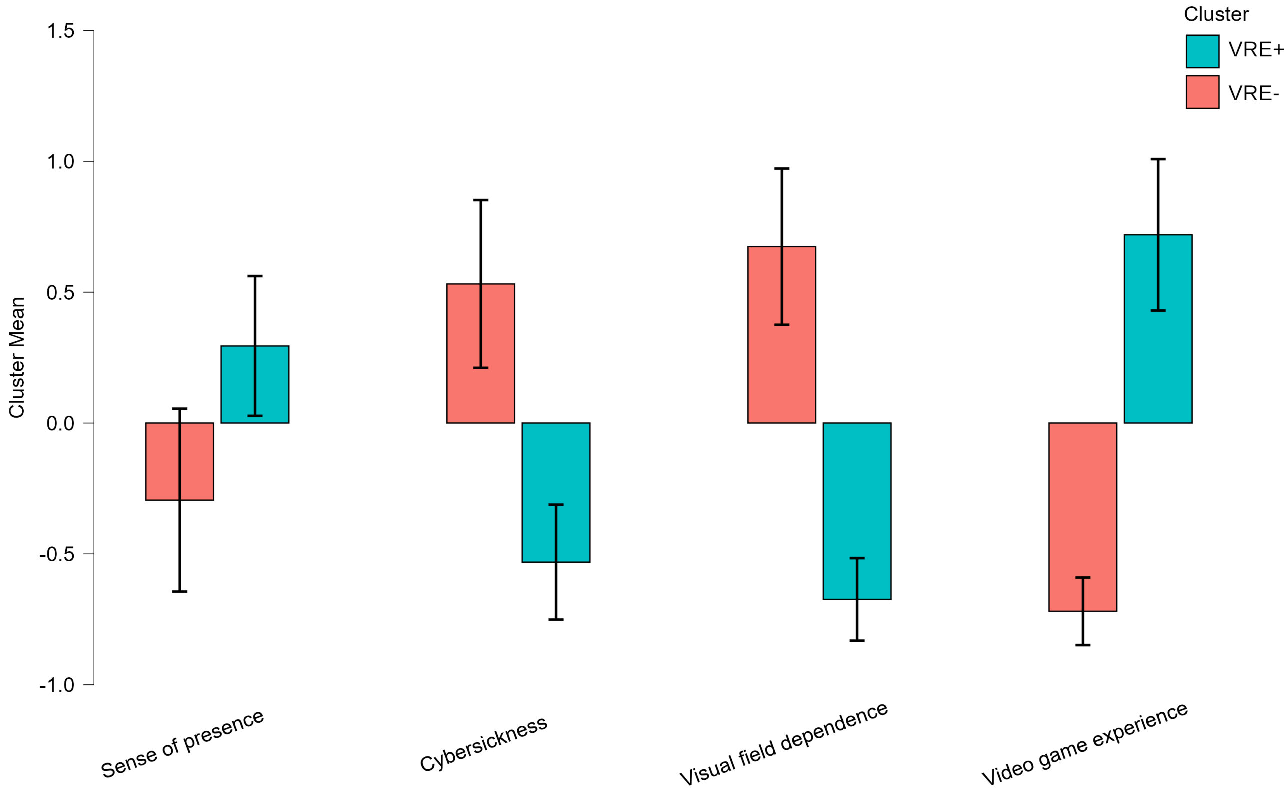

Figure 3. Mean and standard deviation (SD) for each human factor (sense of presence, cybersickness, visual FDI, video game experience) in the VRE + (in orange) and VRE- (in green) cluster (color figure online)

No significant effect of the subjective experience of VR (VRE + vs. VRE−) was found on WCST performance after controlling for age and education. However, education significantly predicted WCST performance: $F_{1,48} = 13.97$, $p < 0.001$. A significant effect of the subjective experience of VR was found on perceived mental effort after controlling for age and education: $F_{1,48} = 6.67$, $p = 0.012$, $\eta^2 = 0.115$. VRE- individuals (2.73 ± 1.5) reported higher perceived mental effort than VRE + individuals (1.84 ± 1.2): $t = 2.58$, $p = 0.012$, 95% CI [0.23, 1.85].

Discussion

The aims of the present study were twofold: (i) to compare executive control performance on a standard neuropsychological test (WCST), performed either in traditional PP or VR modality, and (ii) to determine the origin and impact of human factors (i.e., sense of presence, cybersickness, field (in)dependence and video game experience) as possible contributors to WCST performance and perceived mental effort in the VR modality. Considering our first objective, and in accordance with our hypothesis, neither performance on the WCST nor perceived mental effort was different between the two modalities. Of note, a within-subject design would have been more suitable in order to investigate differences between the two modalities, but learning to test the WCST would have given a ceiling effect here. Inter-individual differences between the two groups were therefore controlled for by using age, education, and level of visual FDI and video game playing as covariates. In the present study, the absence of difference in WCST performance and perceived mental effort between the two modalities was a necessary step in order to i) judge the validity of the implemented test and ii) further explore differences within the VR modality. This validity is amplified by the fact that education was he only predictor of WCST performance. (The absence of age effect is easily explainable by the fact that all participants were young subjects.) In the same vein, the fact that the sense of presence and cybersickness scores measured here were respectfully higher and lower than the reference standards lends validity to the virtual environment. We allow ourselves a digression here to call on VR researchers to systematically report these scores in order to allow inter-study comparisons. Concerning our second objective, the results are less straightforward. In accordance with our hypothesis and in view of the results (correlation matrix and cluster analysis), the four studied human factors seem interrelated. Many of the associations suggested in the literature are found here, confirming the idea that a favorable cognitive profile to VR (i.e., less visual field dependence and more video game experience) positively impact the subjective experience of VR (i.e., more sense of presence and less cybersickness). It is particularly interesting to note that visual FDI emerges as the main factor linking all the others: This variable is not only the only one to be significantly correlated with all the other human factors, but it is also the one with the strongest associations. This is consistent with recent empirical work in the field, where the question of visual dominance, visual FDI and visual down-weighting is crucial for a good adaptation in VR and its inherent sensory mismatch (Fulvio et al. 2021; Keshavarz et al. 2017; Maneuvrier et al. 2021; Weech et al. 2020a, b). What can be said in the context of this study: 1) visual field-dependent individuals tend to be more susceptible to the sensory mismatch

(Kennedy 1975), which results in more cybersickness symptoms, and 2) they tend to be less susceptible to the sense of presence as they are more perturbed by visual flaws in VR and have lesser inhibition skills (Bian et al. 2020; Bloomberg 1965; Hecht and Reiner 2007). Further studies are required, but visual FDI seems to be a strong predictor of an individual ’ s psychophysiology in VR. Finally, it is particularly interesting to see that the strongest association among all these human factors is the negative one between visual FDI and video game experience. This association is, to our knowledge, not documented in the literature. However, it has been found that playing 3D games during the early stages of development might reduce visual field dependence (Levine et al. 2016), and it is possible to argue that many video games involve a strong spatial cognition component, provoking a similar effect. On this matter, spatial cognition could be the missing link between (1) a training effect of video games on visual FDI which is often considered as associated with spatial processes (Boccia et al. 2016; Cian et al. 2011; MacLeod et al. 1986; Nori et al. 2021), and (2) an enhanced formation of the sense of presence, also associated with spatial processes (Wirth et al. 2012). In addition, it can be argued that many video games involve a slight sensory mismatch (an incongruent visual flow in a seated position) which could have the same habituation aspect: Video game players could be trained to rely less on visual cues and (Howarth and Hodder 2008). Of course, it is unsure if video games are more appealing to visual field independent individuals, or if they make their players more field independent. Regardless of the causal direction, which will be hard to assess, making visual field FDI the central human factor connects them all in a coherent way in order to apprehend them as a global VR cognitive profile. However, it remains to be seen how this VR cognitive profile might be favorable or unfavorable to performance. Indeed, among the studied human factors, only cybersickness was directly (and negatively) associated with WCST performance and perceived mental effort in VR. The association found here is weak, but in line with the literature (Gresty et al. 2008; Gresty and Golding 2009; Kennedy et al. 1993; Maneuvrier et al. 2020; Nesbitt et al. 2017; Stanney et al. 2002; Szpak et al. 2019). This result alone should make it necessary to take cybersickness into account for any behavioral assessment using VR: Since these symptoms are linked to poorer performance and not all individuals are equally sensitive to them, the performance obtained should be weighted by the degree of cybersickness experienced. Still, it remains possible that these participants rationalized a poorer WCST performance by attributing it to VR symptoms, so further analysis is needed. Of note, it is interesting to see that the sense of presence was neither associated with WCST performance and perceived mental effort nor correlated with cybersickness, contrary to what has been observed and suggested previously (Maneuvrier et al. 2020; Weech et al. 2019). This might suggest that the virtual WCST task, as implemented in the present study, was not integrated enough to be impacted by this factor, contrary to what happens during a spatial navigation evaluation. Indeed, the interaction with the environment was rather low: The participants had little freedom to bring out a deep sense of presence, explaining the relatively low effect of the latter in this study. Finally, the fact that video game experience was not directly associated with WCST performance and perceived mental effort could be explained by the fact that the sensorimotor component of this task was not very prominent, preventing video game players from transferring their skills. Further studies incorporating stronger visuo-manual skills are required to test this interpretation. Last, but not least, it should be kept in mind that all the studied human factors, if they are not directly associated with WCST performance and perceived mental effort, they are strongly collinear. It is therefore possible that they interact to influence, indirectly, WCST performance and perceived mental effort. Indeed, cluster analysis outlined two different profiles of individuals in VR: the individuals with a good subjective experience of VR (more sense of presence, less cybersickness, less visual field dependence and more video game experience), and those with a poor subjective experience of VR. If both groups did not differ significantly on their WCST performance, individuals with a poor experience of VR did report a heavier perceived mental effort. This is important since perceived mental effort was directly associated with WCST performance in both modalities. Considering this, it is possible to consider that the subjective experience of VR did not directly affect WCST performance because of the large amount and availability of attentional resources among our young participants (age = 24.7 $\pm$ 3.1). In this sense, the subjective experience of VR could have a much stronger impact on the WCST performance of older and/or pathological individuals with lower attentional control resources (boisgontier, stern, young). It can also be argued that a similar effect would occur during a task more demanding in attentional resources. This effect should therefore be tested on a larger sample with lower attentional control resources and/or with another type of task. But even if there is a slight effect of human factors on cognitive performance and perceived mental effort during an assessment, it should be considered, whether the tool is used for diagnostic, rehabilitation, learning, or research purposes.

Conclusion

In conclusion, if VR opens the door to powerful ecological and methodological evaluations, many aspects must be taken into account. This study goes in this direction, by trying to outline a theoretical model aimed at predicting and reweighting cognitive performance in VR. According to this model, an unfavorable cognitive profile to VR, constituted notably but not only by a high visual field dependence and a low or no video game experience will degrade the VR subjective experience (low sense of presence, high cybersickness) which will, in turn, decrease performance through the degradation and/or re-allocation of attentional resources. In addition, this study suggests that field (in)dependence could be a strong predictor of this profile and thus of the subjective experience of VR. Future studies are needed to explore and test this model in more detail, as many questions remain: do different types of video games played have a different impact on the VR experience? Is this model independent of the nature of the task performed and its ecological degree? Is what is true for a WCST true for another neuropsychological test? If the tool continues to develop, it is clearly time to develop standardized environments and establish standards for VR psychophysiology. Without this, cognitive assessments in VR risk being systematically biased: as long as VR is distinguishable from reality, a VR experiment is not a mere transposition of a traditional task but a whole new paradigm which should be regarded as such.

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Ethics approval: This research complied with the tenets of the Declaration of Helsinki and was approved by the CLERS (“Comité Local d’Éthique de la Recherche en Santé” / Local Health Research Ethics Committee, reference: 042020FLE-MAN).

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