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Abstract

Accurately perceiving the gravitational direction is key to successful interaction in our terrestrial environment. In this context field dependence (FD), the importance given to static and/or dynamic visual cues, has largely been discussed. Although first considered a trait, several studies suggest FD be flexible in response to postural or visual contexts and to poor virtual reality user experience. The aim of this study was therefore to determine the influence of a disruptive virtual immersion on the level of static and dynamic FD. Forty-five participants were exposed to a virtual maritime environment for up to 14 minutes. Cybersickness and sense of presence were measured. Before and after virtual immersion, the Rod and Frame Test and the Rod and Disc Test were performed to assess static and dynamic FD respectively. We demonstrated a significant decrease in both levels of FD after immersion in initially more dependent participants. Decrease in static FD was explained by high initial static FD and severe cybersickness, while decrease in dynamic FD was only explained by the initial level of dynamic FD. In this study, we provide evidence confirming FD flexibility, likely reflecting an adaptation process to environmental or individual-related constraints. Yet, static and dynamic FD seem to rely on separate mechanisms, highlighting the necessity to specify which characteristic of visual information (static or dynamic) individuals depend on when assessing their FD. Our results question the reliability of virtual reality for perceptive or motor diagnoses without considering its consequences, specifically in vulnerable populations such as the elderly.

Keywords: Field dependence, Perceptive style, Virtual reality, Cybersickness, Virtual immersion

Author Contributions: H.C. conceived and designed the experiment. L.F. conducted the experiment, collected and processed the data. All authors analyzed and discussed the results, wrote, reviewed and approved the manuscript.

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Introduction

Successful navigation and action in our environment relies on an accurate perception of the gravitational vertical, in order to align our body accordingly (Niehof et al., 2019). To this end, individuals can rely on either a visual, gravitational, or egocentric frame of reference (FoR – Ohlmann, 1988), based on visual, vestibular and somesthesic cues respectively (Isableu et al., 2010). Each FoR is attributed aweight (Ohlmann, 1990), implying the dominance of one of them for performance in tasks requiring geocentric perception. However, the dominance hierarchy of FoR, varies from one individual to another. In this context, different perceptive styles can be distinguished: individuals who strongly rely on visual cues are considered field dependent, whereas those who rather use vestibular and somesthesic cues, are more field independent (Tinajero & Páramo, 1998).

The first approaches to perceptive styles considered them as a trait, characterizing individuals in relation to the way they perceived their environment (Witkin et al., 1967), or their memorizing and problem-solving strategies (Messick, 1976). The most common way to determine one's perceptive style is the Rod and Frame test (RFT – Witkin & Asch, 1948), consisting in a subjective visual vertical estimation while exposed to a tilted frame. The presence of the frame attracts the subjective vertical in the direction of its tilt (frame effect), which may be understood as an optostatic illusion of self-tilt (Dichgans & Brandt, 1978). The magnitude of the frame effect is related to the level of dependence on visual cues (*i.e.* field dependence – FD) on a continuum ranging from extreme field independence to extreme field dependence. From this position, the level of FD can thus be assumed as one of the main causes of individual differences in geocentric perception tasks (Isableu et al., 1998).

Multiple studies have suggested that the level of FD can change relative to the context (Bray et al., 2004; Mahboobin et al., 2005; Maneuvrier et al., 2021; Pavlou et al., 2011). According to the theory of vicarious processes (Reuchlin, 1978), the FoR dominance hierarchy could be modified in demanding situations where the preferred FoR does not support a sufficiently effective response, in order to maximize the chances of success (Ohlmann, 1988; Ohlmann & Marendaz, 1991). Flexibility of FD could therefore reflect an adaptation process in response to various types of constraints simultaneously applied to the individual, while performing a geocentric task. Indeed, Bray et al. (2004) showed a significant decrease in the frame effect when subjects were balancing on a beam in a sharpened tandem stance, compared to less challenging postures. The postural-related environmental constraints could thus lead to a decrease in FD, for instance when postural stability is threatened. In fact, prior studies had

revealed a convergence in postural control when in a tandem stance facing a tilted frame. One interpretation is a down-weighing of visual cues, which could imply a shift towards the gravitational FoR (Brenet et al., 1988; Isableu et al., 1997). It has also been suggested that visual characteristics of the environment can lead to flexibility of FD. One study has notably shown that postural responses to antero-posterior visual flow were reduced after unpredictable motion of the visual scene (Mahboobin et al., 2005). One possible interpretation is that an environment composed of unreliable visual cues could have provoked a down-weighing of these cues in postural control, inducing a transient decrease in FD during a fundamental motor task of geocentric nature.

Unreliable dynamic visual cues are especially present in virtual reality (VR), providing visual information of self-movement, when users are in reality stationary. These immersions can lead to a state of discomfort (cybersickness), commonly thought to be caused by discordance between visual and vestibular/proprioceptive cues (Bos et al., 2008; Rebenitsch & Owen, 2016).The intensity of symptoms varies from one individual to another (Bockelman & Lingum, 2017). Some factors have been shown to be negatively related to cybersickness, such as higher experience with video games (De Leo et al., 2014) or sense of presence (Maneuvrier et al., 2020; Weech et al., 2019), while more severe symptoms were shown in women (Shafer et al., 2017; Stanney et al., 2020), and individuals with higher sensitivity to visual cues (Barrett & Thornton, 1968; Fulvio et al., 2021). Regarding the latter, Hecht & Reiner (2007) argued that that high FD may be related to a lower ability to ignore flaws of the visual scene, hence contributing to discomfort. These assertions regarding flexibility of FD relatively to individual VR user experience are also supported by Maneuvrier et al. (2021). Indeed, their findings showed that individuals with poorer VR-user experience (low sense of presence associated to a high level of cybersickness) became less visually dependent after exploring a real-world-like virtual environment. One hypothesis would therefore be that field dependent individuals are be prone to more severe cybersickness and therefore reduce their dependence on visual cues to minimize their discomfort. However, this study failed to show a significant effect of cybersickness level to explain this adaptative process. This could be explained by the fact that participants would navigate in a virtual environment using a teleportation system, cancelling most of the visual flow, to limit discomfort. Moreover, Maneuvrier et al.'s study determined the level of FD based on the RFT only. This methodology is representative of a recurring issue consisting in the use of the RFT as gold standard to characterize FD while the use of complementary geocentric perception tasks for the assessment of FD could provide

finer results, notably under different visual contexts provided by the environment. Some studies have actually suggested that positioning an individual on the field dependence-independence continuum using the RFT may not be transposable to other spatial perception tasks (Bringoux et al., 2016). Indeed, the role of dynamic visual cues in geocentric task has been discussed as fundamental and distinct from that of static cues (Niehof et al., 2019). To assess dependence on dynamic visual cues (*i.e.* dynamic FD), the Rod and Disc Test (RDT) is classically used (Dichgans et al., 1972 ; Guerraz et al., 1998). In this FD assessment paradigm, the background is a dynamic visual scene composed of dots following a roll movement around the gaze of participant, known to induce optokinetic vection (Isableu et al., 1998).

The primary aim of this study was to determine the influence of a disruptive (*i.e.* unpredictable, visually unreliable and potentially nauseogenic) virtual immersion on the level of static and dynamic FD. We expected a decrease in both levels of FD explained by higher initial FD, and more severe cybersickness. The secondary aim was to assess the relationship between static and dynamic FD, as measured by the RFT and RDT respectively. Given the potential influence of visual-related environmental constraints on FD, it is possible that the attribution of a level of dependence on a given type of visual cues, depends on the intrinsic characteristics of these cues and therefore of the paradigm used. Finally, we planned to investigate additional factors explaining the potential evolution of levels of FD relative to the static or dynamic characteristics of visual cues.

Materials and methods

Population

Forty-five participants (17 females, 28 males, mean age = 22.1 ± 1.7 years old) were recruited by a paper and pencil-based form. They were asked their age, gender, and whether they presented one of the following non-inclusion criteria: vestibular disorders, uncorrected visual impairment, frequent migraines or dizziness, and taking any medical treatment other than a contraceptive pill. Pregnant women were also not included in this study. Women were informed not to be on their menstrual period during the experimental session.

The study was carried out in agreement with legal requirements and international norms (Declaration of Helsinki, 1964). Each included participant gave their written informed

consent to participate in the study. The informed consent form contained information about the voluntary nature of the study and the option 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 as participants. Even though they were informed that they could stop the experiment at any time, none of them chose to.

Experimental devices and virtual environment

The participants were equipped with a VR HTC® VIVE pre head-mounted display (screen: Dual AMOLED 3.6'' diagonal; field of view: 110 degrees; resolution: 1080 * 1200 pixels per eye - 2160 * 1200 pixels combined; Refresh rate: 90Hz; Eye relief: Interpupillary distance and lens distance adjustment).

The virtual environment consisted in a VR-generated, first-person view on a boat (Fig 1). It was created under Unity3D engine specifically for the purpose of our research (Visual Motion VR software, developed by our team). Stationary clouds were added to the background, and the horizon was always clearly visible. VMVR software contains settings for amplitude and frequency of waves and simulated head movements, the latter facilitating the possible occurrence of cybersickness. Pre-tests were led in order to determine settings at which the virtual environment induced moderate but bearable discomfort. Waves were set at 0.7m of amplitude (*i.e.* vertical motion) at two frequencies of 0.3Hz and 0.5Hz. Simulated head pitch and yaw movements were set at a 4deg peak to peak amplitude at a frequency of 0.1Hz. Finally, simulated head roll movements were set at a peak to peak 7deg amplitude, at 0.4Hz.

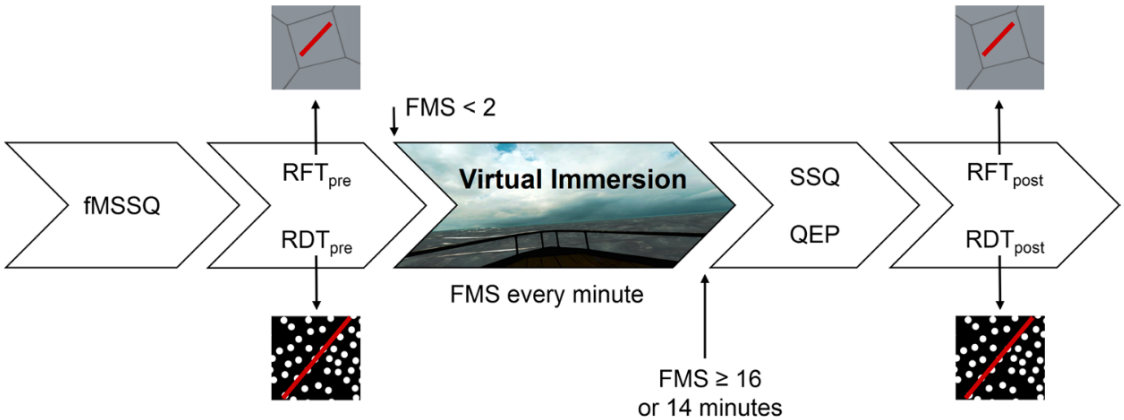

Fig 1 Timeline of an experimental session

Experimental design

First, all participants had to complete the French version of Motion Sickness Susceptibility Questionnaire short form (fMSSQ) in accordance with the method of Vallerand (1989), a reliable tool for predicting individual differences in motion sickness caused by a variety of means of transport, which has been further validated against controlled laboratory motion stimuli. Participants were also asked to inform how many hours per week they spent practicing sport and playing video games.

Second, participants were seated, equipped with the VR-headset and their head held vertical by a chinrest. To assess static FD, the RFT was performed on RVR Virtualis® Software (https://virtualisvr.com/). The display consisted in a 40deg-tilted red rod placed inside an 18deg-tilted gray frame. The instruction was to rotate the rod, using an Xbox 360 controller, until they estimated that it was objectively vertical (*i.e.* aligned with gravity). There was no time limit, but participants were encouraged to answer spontaneously in a reasonable time frame. They were also free to fixate any part of the display. Participants were given 2 blocks of 4 trials, each block corresponding to the tilt directions of the frame (left and right). The direction of the initial tilt of the rod was counterbalanced between blocks. Once the 8 trials were finished and after a 5-minute rest free of the VR-headset, dynamic FD was measured thanks to a virtual RDT on RVR Virtualis® Software. The instructions were identical to the RFT, however the visual scene was composed of white dots following a 30deg/s roll movement on a black background. Participants were given 6 trials (3 for each direction of roll movement). The initial tilt of the rod was of 40deg in the direction of the rotation of the visual scene. For both FD assessment paradigms, participants were given no feedback regarding their performances.

Third, after a 5-minute rest free of the VR-headset, participants were asked to verbalize their current subjective state of discomfort (*e.g.* headache, dizziness, nausea, sweating, hot or cold sensations…) using the Fast Motion Sickness scale (FMS; Keshavarz & Hecht, 2011), ranging from 0 (absolutely no discomfort) to 20 (extreme discomfort). If the verbalized FMS score was strictly under 2/20, the disruptive virtual stimulation could begin. During the virtual immersion, the instructions given to the participants were to stay seated, to keep their hands on their legs or along their body, to concentrate on the virtual environment, and to limit their head movements. Every minute, participants were asked to verbalize an FMS score. The stimulation was discontinued if the verbalized FMS score reached 16/20, or if the participant

asked to stop for any other reason. If none of these criteria were met, the stimulation lasted until its maximum of 14 minutes. The duration of immersion in minutes was noted at the end of the stimulation. Immediately after the virtual immersion, participants were asked to complete the French translation of Simulator Sickness Questionnaire (SSQ; Bouchard et al., 2007) and a French validated Questionnaire of Presence (Questionnaire sur l'Etat de Présence – QEP; Robillard et al., 2002).

Finally, the RFT and RDT were repeated in the same conditions as previously described. The delay between the end of the disruptive immersion and the following RFT and RDT measures was approximately 5 minutes. The course of an experimental session is illustrated in Fig 1. The order of the FD assessment tasks was deliberately chosen to avoid any influence of discomfort provoked by the RDT's visual flow on RFT performance.

All participants with corrected-to-normal vision were asked to wear their glasses or contact lenses during the session from start to end. No participant complained about any form of discomfort or pain resulting wearing glasses under the head-mounted display.

Data processing

Raw data for each participant (fMSSQ score, quantity of sport and video games, RFT and RDT errors, FMS score at each minute, immersion duration, SSQ score, QEP score) were stored in a specific pseudonymised electronic database.

RFT and RDT errors were measured by calculating the angular difference between the objective vertical direction, and the subjective visual vertical. If the rod was tilted in the direction of the frame or of the dots' movement, the errors were noted positive, and in the opposite direction, they were noted negative. For each participant and for each FD assessment paradigm, an average signed score before virtual immersion (RFT_{pre}, RDT_{pre}), and after immersion (RFT_{post}, RDT_{post}) were calculated. Higher scores indicated higher level of FD. Evolutions of scores (RFT_{evol}, RDT_{evol}) were calculated by subtracting pre-measures from post-measures. A positive score indicated an increase in the level of FD, whereas a negative score indicated a decrease.

fMSSQ, SSQ and QEP scores were calculated accordingly to the instructions given by the authors (Bouchard et al., 2007; Golding, 2006; Robillard et al., 2002). In each case, only the

global scores were considered. Higher scores indicated more intense cybersickness (SSQ) and stronger sense of presence (QEP).

Immersion duration for each participant was classified in an interval, expressed in minutes. Three intervals were formed: participants who did not bear more than one minute of immersion [0-2[, those who endured 2 to 13 minutes [2-13[, and those who experienced the totality of the immersion [13-14]. The amount of hours a week playing video games was transformed into an ordinal variable (0h/week: never; 1-10h/week: sometimes; over 10h/week: frequently). The data of 3 participants regarding amount of video games were missing.

Statistical analysis

In order to verify the disruptive nature of the VR immersion, the FMS scores before and at the last minute of VR immersion were compared. Since both FMS scores did not follow normal distributions according to Shapiro-Wilk tests (FMS start: W = 0.65; FMS end: W = 0.85; *p*s < .001), the comparison was performed using a Wilcoxon's signed ranks test.

In order to assess the relationship between the levels of static and dynamic FD, the correlation between RFT_{pre} and RDT_{pre} errors was tested. According to a Shapiro-Wilk test, RFT_{pre} and RDT_{pre} errors did not follow normal distributions (RFT_{pre}: W = 0.95; RDT_{pre}: W = 0.92 ; *p*s < 0.05), the Spearman method was therefore used.

Statistical analyses of RFT and RDT errors were then performed independently. Participants were separated into groups based on RFT_{pre} and RDT_{pre} measures separately, using a k-means clustering unsupervised machine learning algorithm (10 max iterations, 20 random sets, Hartigan-Wong algorithm). The condition for each clustering was to obtain a minimum of two clusters composed of at least 10 participants. This method generated 2 clusters when based on RFT_{pre} errors (FD-: n = 29; FD+: n = 15) and 3 clusters when based on RDT_{pre} errors (FD-: n = 12; FD+: n = 29; FD++: n = 3), from the least to most initially dependent participants. Details on clusters are provided in the results section.

The normality (Shapiro-Wilk test) and homoscedasticity (Levene test) of RFT and RDT distributions were tested for each cluster at each period (Pre and Post). The effects of cluster and period on RFT errors were investigated using a 2 cluster (FD-, FD+) * 2 period (Pre, Post) ANOVA, and pairwise comparisons were performed using post-hoc t-tests with Holm

correction. For RDT errors, since one cluster was very small compared to the others, non-parametrical statistical analyses were chosen. Therefore for each period, RDT-related quantitative data were expressed as the medians (Med) associated to interquartile range (IQR). The effect of period was assessed using a Wilcoxon's signed ranks test on the whole sample. Two Kruskal-Wallis ANOVAs were then used, to compare clusters for their initial errors (RDT_{pre}) and their evolution (RDT_{evol}) separately. Post-hoc pairwise comparisons between clusters were computed using Dunn tests and p-values adjusted with Holm correction.

To explain evolution of visual cues dependency level after VR immersion, general linear models (GLM) were performed independently for each FD test, on RFT_{evol} and RDT_{evol}, using the gaussian method. For both tests, a full model was first generated:

Full model example:

$$FD_{evol} = Sex + Video\ games\ frequency + QEP\ score +$$

$$fMSSQ + Immersion\ duration\ interval + FD_{pre} + SSQ\ Score$$

The application conditions of the GLMs (linearity, residual normality, homoscedasticity, and residual independence) were verified using Rainbow, Shapiro-Wilk, Breush-Pagan and Durbin-Watson tests respectively. All application conditions were respected by both models. Collinearity was tested in each model using the variance inflation factor (VIF). Since fMSSQ and SSQ score presented collinearity (VIF > 7), fMSSQ scores were excluded from the GLMs.

The glmulti selection method was applied to the full model, testing all main effects and pairwise interactions. The Bayesian Information Criterion (BIC) was used to determine the best model to explain both FD evolutions, a lower BIC indicating a better model.

All statistical analyses and graphs were performed using R software (version 4.1.2). The threshold for statistical significance (α) was at 0.05.

Results

Details on the studied sample are provided in Table 1.

Table 1: Descriptive statistics of the characteristics in the studied sample

Characteristic	N = 45[1]
Sex	
Male	28 [62.2%]
Female	17 [37.8%]
Scale of amount of video game practice per week	
Never	16 [35.6%]
Sometimes	19 [42.2%]
Frequently	7 [15.6%]
Missing	3 [6.7%]
Score of motion sickness susceptibility	12 (13) | 0 - 54
Initial level of static FD (deg)	5.21 (3.04) | -1.43 - 14.55
Initial level of dynamic FD (deg)	5.9 (3.5) | 0.1 - 16.3

[1] n [%]; Mean (SD) | Range

Disruptive nature of the VR immersion

FMS scores at last of VR immersion (Med = 5; IQR = 13 were significantly higher than those before VR immersion. (Med = 0; IQR = 0; V = 0; $p < 0.001$). The effect size (Wilcoxon effect size for paired samples) was equal to 0.84, representing large magnitude.

Correlation between RFT_{pre} and RDT_{pre} errors

Results (Fig 2) revealed no significant correlation between both measures (S = 11897; $\rho = 0.22$; $p > 0.05$). Therefore, following analyses pertaining to RFT and RDT were led independently.

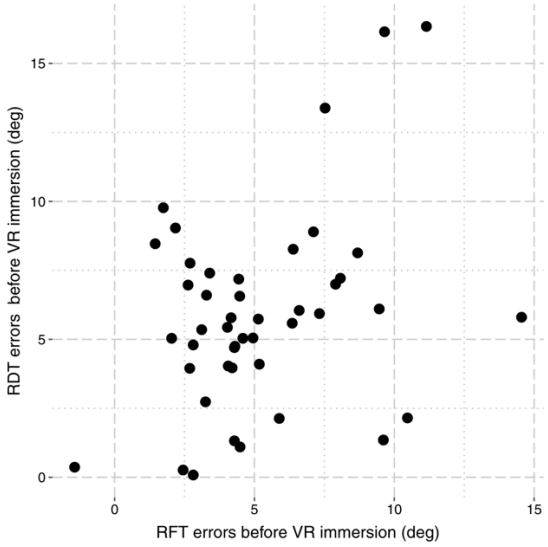

Fig 2 Correlation between RFT and RDT errors before VR immersion

K-means clustering for each FD assessment paradigm

The k-means clustering divided participants into 2 clusters when based on RFT_{pre} errors and into 3 clusters when based on RDT_{pre} errors. Details regarding these clusters are provided in Table 2.

Table 2 Characteristics of k-means-generated clusters based on RFT_{pre} (A) and RDT_{pre} (B)

A. **Characteristic**	**FD-**, N = 30[1]	**FD+**, N = 15[1]	**p-value**[2]
Sex			0.4
Male	20 [66.7%]	8 [53.3%]	
Female	10 [33.3%]	7 [46.7%]	
Scale of amount of video game practice per week			0.8
Never	9 [30.0%]	7 [46.7%]	
Sometimes	14 [46.7%]	5 [33.3%]	
Frequently	5 [16.7%]	2 [13.3%]	
Missing	2 [6.7%]	1 [6.7%]	
Score of motion sickness susceptibility	10 (9) | 0 - 32	15 (18) | 1 - 54	0.4
Initial level of static FD (deg)	3.45 (1.44) | -1.43 - 5.89	8.72 (2.20) | 6.35 - 14.55	<0.001
Score of presence	87 (15) | 62 - 129	76 (14) | 58 - 97	0.021
Score of cybersickness	54 (49) | 0 - 183	59 (60) | 0 - 176	0.8

A. **Characteristic**	**FD-**, N = 30[1]	**FD+**, N = 15[1]	**p-value**[2]

[1] n [%]; Mean (SD) | Range

[2] Pearson's Chi-squared test; Fisher's exact test; Welch Two Sample t-test

B. **Characteristic**	**FD-**, N = 13[1]	**FD+**, N = 29[1]	**FD++**, N = 3[1]	**p-value**[2]
Sex				0.2
Male	10 [76.9%]	17 [58.6%]	1 [33.3%]	
Female	3 [23.1%]	12 [41.4%]	2 [66.7%]	
Scale of amount of video game practice per week				0.001
Never	1 [7.7%]	12 [41.4%]	3 [100.0%]	
Sometimes	6 [46.2%]	13 [44.8%]	0 [0.0%]	
Frequently	6 [46.2%]	1 [3.4%]	0 [0.0%]	
Missing	0 [0.0%]	3 [10.3%]	0 [0.0%]	
Score of motion sickness susceptibility	12 (15) 1 - 54	12 (12) 0 - 54	2 (1) 1 - 3	0.4
Initial level of dynamic FD (deg)	2.1 (1.5) 0.1 - 4.1	6.6 (1.4) 4.7 - 9.8	15.3 (1.7) 13.4 - 16.3	<0.001
Score of presence	85 (15) 59 - 115	83 (16) 58 - 129	79 (13) 70 - 94	0.8
Score of cybersickness	53 (51) 0 - 176	59 (56) 4 - 183	41 (29) 22 - 75	0.8

[1] n [%]; Mean (SD) | Range

[2] Fisher's exact test; One-way ANOVA

Effect of the VR immersion on RFT errors

The 2 cluster * 2 period ANOVA (Fig 3) revealed significant main effects of cluster ($F = 76.57$; $p < 0.001$; $\eta_g^2 = 0.61$) and period ($F = 11.24$; $p < 0.01$; $\eta_g^2 = 0.031$), and a significant interaction ($F = 10.43$; $p < 0.01$; $\eta_g^2 = 0.03$). RFT errors for FD+ were significantly higher than FD- at Pre (Mean ± SD: 8.72 ± 2.20 vs. 3.45 ± 1.44 respectively; $p_{adj} < 0.001$) and at Post (Mean ± SD: 7.43 ± 2.54 vs. 3.43 ± 1.39 respectively; $p_{adj} < 0.001$). In addition, a significant decrease in RFT errors between Pre and Post was shown for FD+ only ($p_{adj} < 0.01$).

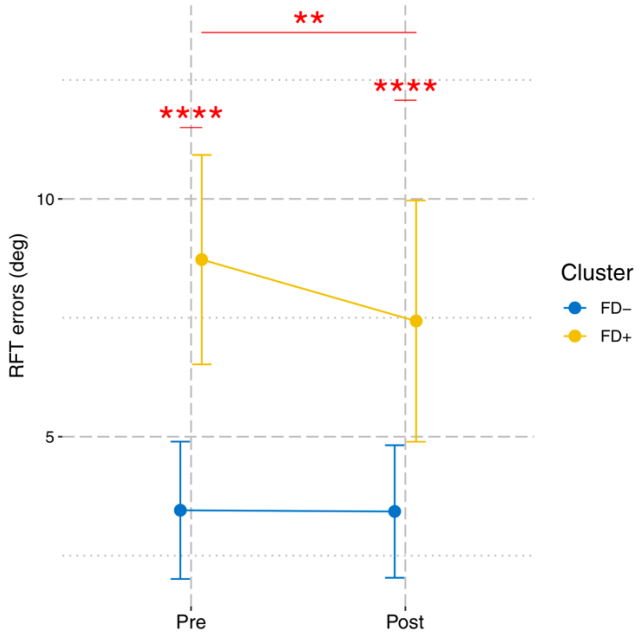

Fig 3 RFT errors before (Pre) and after VR immersion (Post) for each cluster (**: $p < 0.01$; ****: $p < 0.0001$)

Effect of the VR immersion on RDT errors

RDT_{pre} errors (Med = 5.73; IQR = 3.18) were significantly higher than RDT_{post} errors (Med = 4.20; IQR = 3.35; V = 834; $p < 0.001$) in the entire sample ignoring clusters. The magnitude of the Wilcoxon effect size for paired samples was large (0.53). The Kruskal-Wallis ANOVA on RDT_{pre} errors revealed a significant effect of cluster ($\chi^2 = 31.2$; $p < 0.001$; $\eta^2 = 0.69$, FD- having significantly lower RDT_{pre} errors (Med = 2.13; IQR = 2.85) than FD+ (Med = 6.1, IQR = 1.97; Z = 4.79; $p_{adj} < 0.001$) and FD++ (Med = 16.2; IQR = 1.48; Z = 4.40; $p_{adj} < 0.001$). In addition, RDT_{pre} errors for FD+ were significantly lower than FD++ (Z = 2.01; $p_{adj} < 0.05$). Comparisons between RDT_{pre} and RDT_{post} errors in each cluster (Fig 4) revealed a significant decrease of errors for FD+ only (RDT_{pre}: Med = 6.10; IQR = 1.97 and RDT_{post}: Med = 4.87; IQR = 1.92; V = 402; $p_{adj} < 0.001$). The magnitude of the Wilcoxon effect size for paired samples was large (0.74).

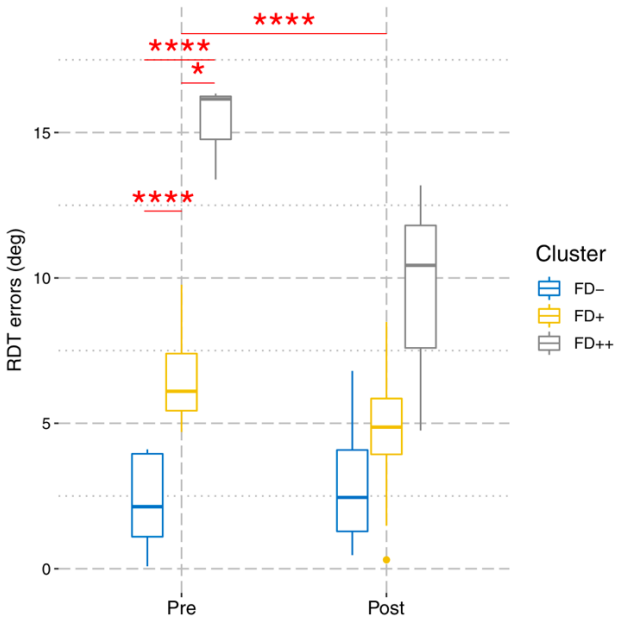

Fig 4 RDT errors before (Pre) and after VR immersion (Post) for each cluster (*: $p < 0.05$; ****: $p < 0.0001$)

The Kruskal-Wallis ANOVA on RDT_{evol} errors (Fig 5) revealed a significant effect of cluster ($\chi^2 = 17.2$; $p < 0.001$; $\eta^2 = 0.36$). Results showed that RDT_{evol} errors was significantly higher in FD- (Med = 0.3; IQR = 0.72) than in FD+ (Med = -1.82; IQR = 2.32; Z = -3.3; $p_{adj} < 0.01$) and FD++ (Med = -5.91; IQR = 2.83; Z = -3.52; $p_{adj} < 0.01$). No significant difference was found between FD+ and FD++ (Z = -1.90; $p = 0.06$), despite a tendency.

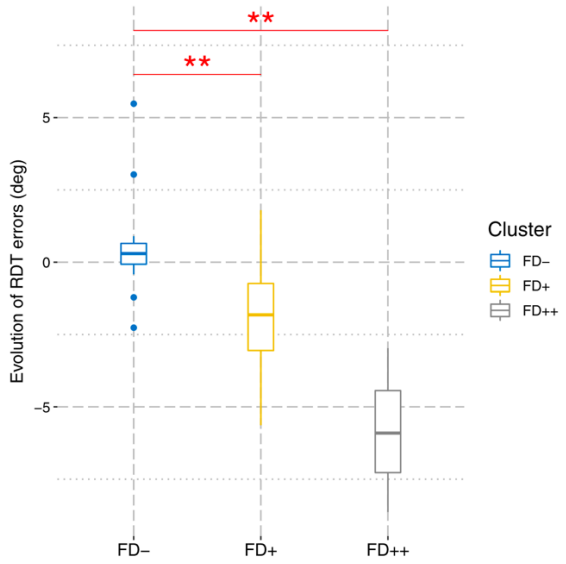

Fig 5 Evolution of RDT errors after VR immersion for each cluster (**: $p < 0.01$)

General Linear Models on RFT_{evol} errors

The best model to explain RFT_{evol} errors with a BIC of 149.11 is detailed below:

$$RFT_{evol} = 0.73 - 0.144RFT_{pre} - 0.001RFT_{pre} * SSQscore$$

RFT_{pre} and the RFT_{pre} * SSQ score interaction were revealed as significant (respectively $p < 0.05$ and $p < 0.01$). Details on this model are given in Table 3A.

General Linear Models on RDT_{evol} errors

The best model to explain RDT_{evol} errors has a BIC of 191.67, and is detailed below:

$$RDT_{evol} = 1.330 - 0.465RDT_{pre}$$

The effect of RDT_{pre} was significant ($p < 0.001$). Details on this model are provided in table 3B.

Table 3: Explanatory factors of RFT_{evol} (panel A) and RDT_{evol} (panel B) models associated with betas, confidence intervals and *p*-values.

A. **Characteristic**	**Beta**	**95% CI**[1]	**p-value**
(Intercept)	0.73	0.08, 1.40	<0.05
Initial RFT errors (deg)	-0.14	-0.26, -0.02	<0.05
Initial RFT errors (deg) * Score of cybersickness	0.00	0.00, 0.00	<0.01

[1] CI = Confidence Interval

B. **Characteristic**	**Beta**	**95% CI**[1]	**p-value**
(Intercept)	1.33	0.29, 2.4	0.016
Initial RDT errors (deg)	-0.47	-0.62, -0.31	<0.001

[1] CI = Confidence Interval

Discussion

The first aim of this study was to determine the influence of a disruptive virtual immersion on the level of static and dynamic FD. In accordance with our hypothesis, our findings have

revealed a decrease in these FD levels after VR immersion, reflected by a reduction of RFT and RDT errors on the sample level. However, our comparisons across clusters for each task indicated significant decrease in RFT and RDT errors (*i.e.* static and dynamic FD) only in initially more dependent participants. VR immersion therefore impacted their way the initially more visually dependent participants interacted with their gravitational environment. Overall, these findings highlight perceptive consequences of a VR immersion, and call for their consideration in recreational as well as professional usage. While the use of virtual reality is becoming increasingly common to clinically diagnose perceptive and motor behaviors, the perceptive modifications induced by exposure to virtual reality is rarely taken into account. Therefore, our results could question the reliability of VR as a technology for diagnoses, especially in vulnerable individuals who are susceptible of being disturbed (from a perceptive or motor point of view) by visual flow generated by immersive environments. Vulnerability to immersive environments is especially present in elderly individuals who strongly rely on visual information despite their decreasing eyesight.

The measure of the level FD for a given individual, however, depends on the FD assessment paradigm. Indeed, we found an absence of correlation between initial performances in the RFT and RDT. In accordance with our second hypothesis, this indicates that the visual characteristics of the environment in which a geocentric perception task is conducted may be considered as a visual-related environmental constraint capable of influencing geocentric performance. Moreover, flexibilities of static and dynamic FD were not explained by the same factors, as shown by our GLMs. While static FD evolved in relation to high initial static FD associated with severe cybersickness, dynamic FD flexibility was explained by high initial dynamic FD only. These findings partly invalidate our predictions, though they do suggest that flexibility of static and dynamic FD do not seem to rely on the same mechanisms. Therefore, when characterizing individuals for their FD it is important to specify which nature of visual cues (*i.e.* static or dynamic) they are dependent on. The concept of FD can be considered situational, and dependent on the characteristics of the considered visual cues.

The observed differences between flexibility of static and dynamic FD could be related to the nature of the disruptive visual stimulation used in this study. On the one hand there were no visual cues providing information on verticality, and the only visual orientation was the horizon which was subject to simulated motion. On the other hand, the dynamic nature of the stimulation was enhanced by simulated head rotations. From this perspective, the exposure to dynamic visual cues alone, may have sufficed to affect dynamic FD, as it had already been

shown with the use of optokinetic and dynamic virtual stimulation (Pavlou et al., 2011). Another hypothesis is that dynamic FD may not be a factor contributing to cybersickness. In order to investigate this, we performed *a posteriori* a Spearman correlation between RDT_{pre} and SSQ measures, which indicated no significant correlation between these variables ($S = 13805$; $\rho = 0.09$; $p > 0.05$). One possible interpretation could be that flexibility of dynamic FD may not constitute an effective adaptation process to maintain the integrity of the individual during VR immersion. Finally, the differences between static and dynamic FD flexibilities may have arisen from visual strain. Indeed, visual fatigue is a factor contributing to cybersickness and is closely linked to VR by its virtual nature (Rebenitsch & Owen, 2021; Souchet et al., 2021; Ukai & Howarth, 2008). It is possible such VR-induced fatigue had a stronger impact on RDT performance since this paradigm contains visual flow, as opposed to the RFT. However, this hypothesis remains unanswered. Future studies should therefore compare the potential effect of visual strain on the use of visual cues between both FD assessment paradigms. In general terms, although the initial levels of FD were somewhat explanatory of both FD flexibilities, the observed differences in the mechanisms of static and dynamic FD seem to confirm the suggestion that the RFT may not be the gold standard to characterize one's perceptive style in all situations (Bringoux et al., 2016). Our findings suggest that measures of FD are situational, and that performance in a visual geocentric task should be interpreted with regard to the characteristics of the visual environment. For more precise interpretation of the reliance on visual cues during a task, future studies could assess FD using a very similar visual background to that encountered during this task.

Our results have shown that flexibility of static FD was explained by a high-level initial FD associated to severe cybersickness in our study, implying that such a process would be the indicator of an ongoing adaptation to reduce an already high level of discomfort for the most dependent individuals, as suggested by Maneuvrier et al. (2021). It is possible that field independent participants did not need to change their reliance on static visual cues as they were not vulnerable to the virtual immersion due to their field independence, or they may have been unable to because of a plateau effect in their field independence. This interpretation is in contradiction with that of Weech et al. (2020), who suggested that the ability to down-weigh visual cues could be an indicator of low susceptibility to cybersickness. This disagreement could be explained by the methodology used in Weech et al.'s study, which indirectly assessed a form of sensory re-weighing in a postural task during the presentation of visual flows of different amplitudes, rather than direct measures of the level of FD. According

to previous studies, however, the perceptive adaptation shown in our study does not seem to be immediately effective, as static field dependent subjects, who presented significant decrease in static FD, are more prone to cybersickness (Fulvio et al., 2021; Hecht & Reiner, 2007). This raises the question of whether the perceptive adaptations to VR immersion are short and quickly reversible, or whether they rather last in time. Our ongoing studies are therefore focusing on durability of static FD flexibility and its effects on cybersickness over time.

Conclusions

Overall, our findings provide evidence that FD is subject to a form of intra-individual variability. This modification in the use of visual cues could be the illustration of a vicarious process of FoR in geocentric perception. We propose that such perceptive adaptations during a VR immersion are a response to environmental and individual constraints. The independence between RFT and RDT errors highlight the influence of visual-related environmental constraints, which seem to have similar effects to postural-related environmental constraints as shown by Bray et al. (2004). Therefore, it seems necessary to specify which characteristic (static or dynamic) of visual information individuals are dependent on, when assessing their FD. In previous works, Maneuvrier et al. (2021) had suggested user experience as an individual constraint influencing FD flexibility. Our findings however, revealed no influence of sense of presence on FD, possibly explained by the passive nature of our virtual task. On the other hand, our results did confirm that severe cybersickness was related to decrease in static FD, but only when associated to a high initial level of static FD. This implies that FD could be considered as an individual-related constraint in a virtual immersion context, as much as cybersickness is. Given the differentiated effects of this discomfort on static and dynamic FD, is likely that all natures of constraints are able to interact and thereby modify the FoR dominance hierarchy. Some studies have suggested a switch towards a preferred gravitational FoR for postural control (Brenet et al., 1988; Isableu et al., 1997), although this assertion remains to be confirmed. Furthermore, the adaptive processes following VR may not only be of perceptive nature. Provided the intrinsic relationship between sensory perception of the gravitational direction and postural behavior, further studies should investigate the posture-locomotor repercussions of these perceptive adaptations to virtual immersion.

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