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Ocular vergences measurement in Virtual Reality: A pilot study

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Abstract

In this study, we investigated the value of using virtual reality to evaluate ocular vergence performance.

We used a virtual reality device with an integrated eye-tracking system to create virtual environments that simulated far and near vision conditions and assessed ocular movements. We compared the maximum angular deviation compensated by the visual system or the vergence scores of the participants in the virtual environments with the vergence scores obtained with a prism in real environment, i.e. with the technique usually used for clinical assessments. We also compared a simple virtual environment with a complex virtual environment by creating landscapes.

The vergence scores obtained for divergence and convergence with the virtual reality device were very similar to those obtained using prisms. This suggests that the virtual environments efficiently stimulated vision conditions in 3 dimensions. Our results also support the idea that modulating the angular deviation of the projected image in the virtual reality headset is a satisfactory way of inducing ocular vergences. The amplitudes of fusion were better in the virtual conditions, suggesting that the controlled virtual environments provided better conditions for measuring vergence movements. We suggest that the headset made it easier for the participants to focus their attention during the task.

Furthermore, the virtual reality device induced a better relaxation of convergence in participants with high convergence abilities and prevented the underestimation of divergence abilities in these participants. This last result suggests that this type of virtual reality mechanism could be helpful in the future for remediating vergences-related disorders.

Key Words

Vision; Orthoptist; Ocular vergences; virtual reality; vergence mechanism, amplitude of fusion; optometric evaluation; accommodation-convergence system

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Introduction

To perceive an object correctly, several conditions must be met. First, the image of the object must be projected onto the central area of the retina of both eyes, i.e., the fovea, which is the area that offers the best visual resolution. Second, the visual system must integrate the images from the two foveas into a single final binocular image by means of binocular fusion (Blake & Wilson, 2011, Howard & Rogers, 1995). Third, the ocular system must remain stable until high-level cognitive processing has taken place and object identification is achieved (Deveau, Lovcik & Seitz, 2013). Furthermore, the visual system must constantly adapt to the environment, which is complex, dynamic and unpredictable. Consequently, many regulatory processes are involved in dynamic vision, in particular in the case of binocular oculomotor coordination during and after gaze shifts (Alvarez & Kim, 2013; Sreenivasan & Bobier, 2014) Among the oculomotor coordination movements, ocular vergences can be defined as disjunctive ocular movements that make it possible to maintain binocular vision when the object of interest is moving away from or towards the viewer. When the object of interest moves away, the angle at which it projects onto the two retinas changes and the images of the object are formed on both nasal retinas. A divergent angular movement of the two eyes is then needed in order to re-establish foveal projection. By contrast, when the object is approaching, an angular convergence movement of the two eyes is required (Duwaer, & Van Den Brink, 1981; Otero-Millan, Macknik, Martinez-Conde, 2014). To reduce the latency of eye movements in response to visual changes, such as an object coming closer, the brain automatically produces a first response to some specific stimuli (Sergienko & Nikonenko, 2015; Wallach & Norris, 1963; White & Munoz, 2011). This automatic response to near vision cues involves the triadic accommodation - convergence - pupil system (Mays, Porter, Gamlin & Tello, 1986).

Indeed, the convergence-accommodation system can be recruited by analyzing the focal distance. The primary visual cortex is capable of automatically calculating the distance of the object fixated by the viewer on the basis of angular analyses of the incident light on the retina (see Zhou, Zhang & Fang, 2021 for a review). As poor focusing also induces a loss of visual resolution, the primary visual cortex also interprets visual blur as a indicating a change in focal distance (Buehren & Collins, 2006; Kruger & Pola, 1986). In the case of cues suggesting a focalization error, the cortex triggers accommodation in order to rectify the focus. In humans, lens accommodation is linked to accommodative convergence by the ratio $(AC)/A$ [(Accommodative Convergence)/Lens Accommodation]. An accommodation of 1 diopter generates both convergence of between 3 and 4 prismatic diopters (Ripps, Chin, Siegel & Breinin, 1962) and a reduction in pupil size (May, Warren, Bohlen, Barnerssoi & Horn, 2016). Angular changes in image projection onto the retina are also responsible for the triggering of the convergence-accommodation-pupil “triad” by the binocular cells of the primary visual cortex, which detect changes in angular disparity between the two eyes and the loss of stereoscopy and fusion associated with these changes (Casagrande, Boyd, 1996). By contrast, when an object moves away from the viewer, the convergence-accommodation-pupil system relaxes, allowing divergence to restore binocular fusion. While it is possible to intentionally generate a convergence movement, it is not possible to do the same for divergence, which occurs only when the convergence-accommodation system is relaxed (May, Warren, Bohlen, Barnerssoi & Horn, 2016).

Divergence corresponds to a sort of default mode of vision adapted to far vision. However, in modern human society, near vision is permanently active. Most humans work at a computer on a desk all day long and live in cities. In their leisure time, they continue to use screens to interact on social networks. Consequently, the near vision mechanisms remain permanently active. This excessive reliance on near vision could explain the large numbers of vergence regulation disorders that clinicians have to deal with, especially esophoria and accommodation convergence spasms (Hayes, Sheedy, Stelmack, & Heaney

2007; Sheedy & Shaw-McMinn, 2003). In these dysregulations, it is indeed difficult to restore the balance between divergence and convergence, as divergence cannot easily be solicited when convergence remains permanently active due to a spasm (Cooper, 2011; Sergienko & Nikonenko, 2015).

However, while the enthusiastic use of digital technologies has brought about new clinical challenges by modifying human behavior, it has also opened up new possibilities. In this study, we decided to examine whether virtual reality could help relax the accommodation-convergence system by creating conditions of far vision even in a tiny space. We also examined if the use of virtual reality could permit more accurate vergence measurements as it makes it possible to create more controlled environments than real conditions. We therefore compared the measurement of vergence abilities for far and near vision in a virtual reality condition incorporating an eye-tracking system to traditional clinical prism-based measures of vergence in real conditions (Cooper, Burns, Cotter, Daum, ..., & Scheiman, 2011). By deflecting the light, the prisms disrupt fusion, thus constraining the brain to generate a compensatory movement to restore fusion. When the deflection can no longer be compensated for, the subject experiences diplopia. The measured vergence corresponds to the maximum angular deflection that the brain is able to compensate for by producing a vergence movement. To obtain a similar type of measure in virtual reality, we used a virtual reality headset with an incorporated eye-tracking system. One of the advantages of the virtual reality headset is that it is equipped with two groups of lenses that project onto each eye independently. We designed a program that modified the projection angle of the lenses into each eye and stimulated vergences based on angular deflection in a very similar way to the prisms. The technique we used to induce vergences is presented in Figure 1.

To examine how efficiently virtual reality systems are able to simulate far and near vision conditions, we also created two types of environments: simple and complex. In the simple environments, the subject perceived a black ball suspended at various distances. For the complex environments, we created complex landscapes. The aim was also to assess whether the cognitive interpretation of the environment modifies the effectiveness of the simulation by inducing the ideas of far vision, in one hand, and causing participants to relax in the second hand. Indeed, the perception of natural landscapes is judged relaxing and produces positive emotions (Groen, 2020).

A meta-analysis (Howard, 2017) has shown that virtual reality is very efficient in simulating controlled environments for motor reeducation and that participants are motivated by this playful reductional technique. Many studies have shown that virtual reality can be successfully used to simulate environments for the reeducation of general motricity (Bergeron, Lortie & Guitton, 2015; Lee, 2013; Yen, Lin, Hu, Wu, ...& Lin, 2011). Some studies have also explored the potential of virtual reality for visual applications (see Levi, 2023 for a review). These studies have mainly examined the use of virtual reality for treating amblyopia (Godinez, Martin-González, Ibarrodo & Levi, 2021) and sensorial abnormalities such as stereoscopic difficulties (Levi, Li & Ying, 2019) and have shown a beneficial effect of virtual stimulation on impaired sensory functions. However, few studies have examined the measurement and/or reeducation of ocular vergences. Mishra et al., (2020) compared eye movements with the virtual reality headset with electro-oculographic measures of oculomotricity. They showed that it was possible to assess oculomotricity using a virtual reality device coupled with an eye tracker. Unfortunately, they did not try to assess the vergences induced by angular movements. They only examined the vergences produced by moving the target into the virtual environment by modifying the distance to it and observed strong interindividual variability. We hypothesized that by using a process based on the same mechanisms as those habitually mobilized using prisms in clinical settings, we should obtain very similar measures to those observed in real conditions. These measures could even be more precise because the environment presented in the headset is controlled. Furthermore, we wanted to

examine whether the far landscapes we presented for the far vision virtual reality condition have a relaxing effect due to the cognitive interpretation of distance compared to the measurement made at 5 m in the real environment.

Material and Method

Participants

A total of 50 psychology undergraduate students (46 female, 4 male) from the University of Clermont Auvergne (UCA) participated in the experiment to gain course credits. They gave their consent to participate in the experiment, which was approved by the UCA research ethics committee (IRB00011540-2022-59).

Material

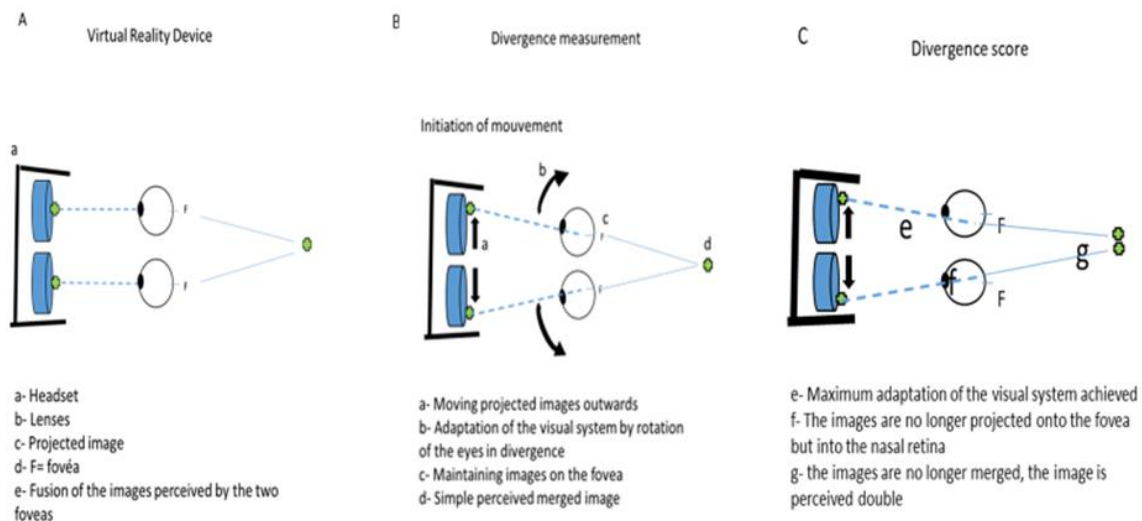


Figure 1. Method of vergence induction with the virtual reality headset; **A:** Initial position of the device. **B:** Initiation of divergence movement through the angular movement of the lenses; **C:** Obtention of the divergence score with the onset of diplopia as the participants can no longer compensate for the angular movement.

For the virtual reality tasks, we used an HTC Vive Pro Eye virtual reality headset with an integrated TOBII eye-tracking system to deliver the stimuli and record the ocular responses. This material was associated with the “Steam VR” and “Unity” software, which was used to code the different virtual environments. We created complex and simple visual environments. The complex environments and the headset are presented in Figure 1. Our aim was to simulate ecological visual conditions for both near (a table with a book at a distance of 40 cm) and far vision (a vast landscape) in order to stimulate both the central and the peripheral retinas. The simple visual environments consisted of a black ball presented suspended in a sort of corridor at a distance of 40 cm for the near vision condition and 5 meters for the far vision condition. The size of the ball was not corrected for distance, so it appeared to be smaller in far vision than in near vision. The angular resolution of all stimuli was greater than 1.5’ or .18 Log MAR

to avoid excessively stimulating the accommodation processes. All these environments were lit to correspond to photopic vision conditions ($> 10 \text{ cd/m}^2$). The visual stimuli used for the measurement in the real condition with prisms were near (40 cm) and far (5 m) optotypes that were projected on a screen with an angular resolution of 1.5'. We used a Berens prism to induce vergences.

Finally, we created a program to extract the participants' vergence scores from the virtual reality setup. The score was calculated as the angular deviation from the final angular deflection of the lenses. We then converted these scores into prismatic diopters to compare them with the scores obtained with the prisms. We chose to use a deflection-based score as to assess vergence scores with the prism-based technique.

Procedure

The participants were welcomed in a quiet room and informed of the types of task they would perform. After giving their consent, they were seated on an adjustable armchair. We ensured that they were well positioned with their feet resting on the floor. We asked them to indicate if they feel any discomfort during the task and clearly informed them that they could stop if this was the case.

We first measured the participant's divergence and convergence abilities with the Berens prism by using a computer to project the stimulus onto a wall-mounted screen at a distance of 5 m for the far vision condition and 40 cm for the near vision condition. When the participant was ready, the experimenter placed a prism on his or her face, with its base in the nasal position for divergence and in the temporal position for convergence, and asked "Is the optotype double or single?" As long as the participant answered "single," the experimenter increased the prismatic power in steps of 2 diopters. When the participant answered "double", the experimenter stopped and noted the prismatic power that triggered diplopia.

We then equipped the participant with the virtual reality headset and carried out a 5-point calibration. When the participant was ready, he/she pressed the joystick to start the task. The first environment then appeared, initially with a fixation point that the subject was asked to look at. After a fixation time of 1s, the fixation point disappeared and the task began. The participant was asked to press the joystick as soon as he/she experienced diplopia at the location of the fixation point. The computer recorded the angular deflection of the lenses at the time when the participant pressed the button.

All the participants first performed the 4 divergence tasks: the complex visual environment in near vision, then in far vision, and the simple visual environment (ball) for near and far vision. The exact same procedure was then repeated but with the convergence movement.

We extracted and converted the vergence scores for all the tasks into prismatic diopters to permit comparisons with the measures obtained with the prisms.

Results

Vergence performance

The mean vergence scores obtained with the 3 visual environments (complex virtual environment; simple virtual environment, and real environment) for the different distances are presented in Figure 2. The repeated-measures ANOVA on these mean scores showed no main effect of environment type,

either for the convergence scores, $F(2, 47) = 1.72, p = .189$, or for the divergence scores, $F(2, 47) = .78, p = .46$. As different factors may be involved in explaining vergence performance at 40 cm compared to vergence performance at 5 m, we examined these two distances separately. These analyses confirmed that participants' performances were similar irrespective of the environment for convergence performance at 40 cm, $F(2, 47) = 1.30, p = .27$, and 5 m, $F(2, 47) = 1.71, p = .18$, respectively. Concerning the divergence score, we obtained no effect of environment on scores at 40 cm, $F(2, 47) = 1.96, p = .12$, but a significant environment effect on divergence performance at 5 m, $F(2, 47) = 5.70, p = .005$. The analyses using a Student t test showed that participants had more difficulties in the simple virtual environment condition than in the complex virtual environment, $t(46) = 2.17, p = .035$, and real environment $t(46) = 4.28, p < .001$. However, there was no difference between the real environment and the complex virtual environment ($p = .80$). It simply seems that the reduction in the perceived size of the stimulus with distance had a negative influence on the divergence score in the simple virtual condition. To conclude, if we consider the vergence abilities globally, our analyses suggest that participants behaved similarly in the three environment conditions. Therefore, it seems that the method of measuring vergence abilities with virtual reality provides results that are very similar to those obtained with the traditional technique used for vergence examination in real conditions with the Berens prism.

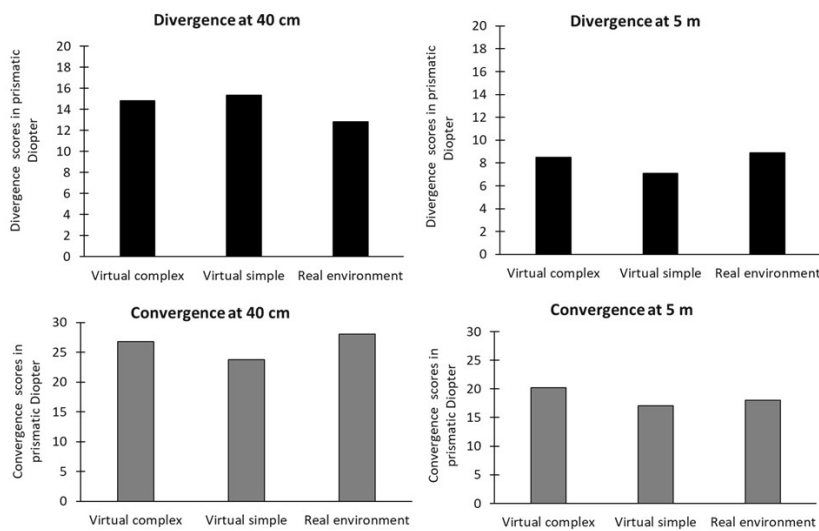


Figure 2. Vergence score

Amplitude of Fusion

To further examine the impact of virtual reality on vergence examination, we calculated the mean amplitude of fusion (convergence score + divergence score) for the three types of environments (simple virtual, complex virtual and real). Once again, we examined the two distances separately. The amplitudes of fusion are presented in Figure 3. This time, our ANOVAs revealed a main effect of environment type at 40 cm, $F(2, 47) = 5.94, p = .005$, (effect size: $\eta^2 p = .20$). Participants had poorer fusion in the real environment with the prisms ($M = 31.39$ diopters (D); $SD = 12$ D) than in the complex virtual environment ($M = 41.6$ D; $SD = 18$ D), $t(48) = 3.33, p = .002$, or the simple virtual environment ($M = 38.6$ D; $SD = 25$ D, $t(48) = 1.74, p = .08$). Consequently, the virtual reality setting provides better conditions for near vergence measurement than real conditions. Concerning the 5-m distance, we also found a significant effect of environment type, $F(2, 47) = 3.52, p = .038, \eta^2 p = .13$. The t -tests revealed that the simple virtual condition ($M = 24.29$ D; $SD = 12$ D) was the worst condition for stimulation and differed from the complex virtual environment ($M = 28.5$ D; $SD = 13$ D; $M(\text{real}) = 26.9$; $SD = 11$) $t(48) = 2.21, p = .03$, but not from the real environment $p = .29$. There was no difference between the complex

virtual and real environments ($p = .56$). Once again, this effect of the simple virtual environment might simply be due to the reduction of the stimulus size with distance.

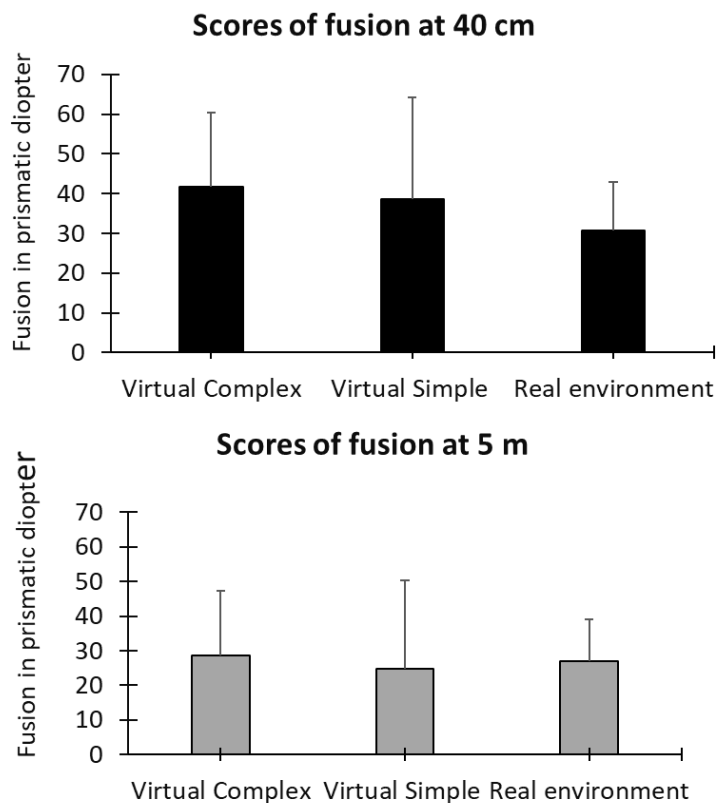


Figure 3. Amplitude of fusion

Analyses as a function of participants' convergence profiles

Examining the results, we observed that the measures of convergence were quite similar irrespective of the experimental setting. Only the divergence scores varied slightly across the conditions. The reduction of the size of the stimulus with distance in the simple visual condition seems to explain the poorer far divergence scores, but does not explain the better fusion observed in near vision in the virtual reality environment. Indeed, this improved fusion observed with virtual reality seems to be linked to better divergence scores. As divergence depends primarily on the relaxation of convergence, and as we observed considerable interindividual variability in the convergence scores, we decided to divide our participants into three different groups as a function of their near convergence ability in real conditions. We then conducted separate analyses for participants with poor near convergence scores, i.e., lower than 20 D (16 participants), participants with typical scores, i.e., between 20 and 30 D (15 participants) and participants with high scores, i.e., greater than 30 D (17 participants). Concerning divergence at 40 cm, the divergence scores for the three groups of participants are presented in Figure 4. Our analyses revealed no main effect of environment, $F(2, 90) = 2.39$; $p = .10$. However, we did find a main effect of convergence ability, $F(1, 45) = 4.62$, $p = .015$, $\eta^2 p = .17$. The higher the convergence was, the greater the divergence. This is not surprising because fusion performances results from both divergence and convergence abilities. More interestingly, we found a significant interaction between convergence ability and type of environment, $F(4, 90) = 5.77$, $p < .0001$, $\eta^2 p = .20$. The post-hoc Bonferroni analyses showed that this interaction was significant only for the poor convergence group compared to the high convergence group ($p = .012$), but not for the typical group compared to the other two ($p > .05$). A closer

examination of the results using a Student *t*-test revealed that there was no effect of environment for the participants with poor convergence abilities. These participants performed similarly in all the environment conditions (all $p > .05$). The participants with typical convergence abilities tended to obtain better divergence scores with the simple virtual condition than in the real condition ($t(14) = -2.18, p = .046$). Finally, the participants with high convergence abilities obtained better divergence scores in the two virtual conditions than in the real conditions, i.e., for both the complex and simple virtual environments ($t(16) = 2.83, p = .012, t(16) = -3.86, p = .001$, respectively). We found no differences between the two Virtual environment conditions. To sum up, the virtual reality setting allows a more precise measurement of fusion in subjects who have strong convergence. It seems that the virtual reality setting helps people to relax their near convergence better and prevents divergence underestimation in near vision conditions.

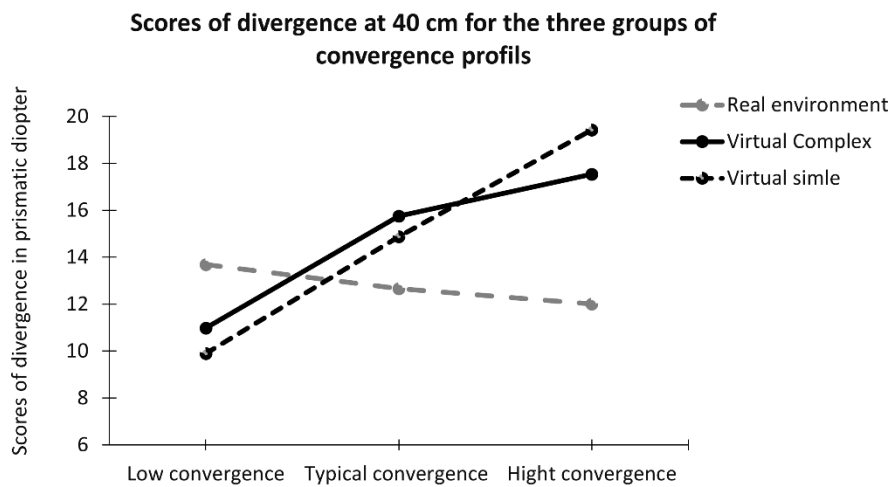


Figure 4. Separated analyses of convergence profiles

With regard to divergence at 5 m, the analyses confirmed the main effect of environment that we had previously found for participants with poorer divergence scores in the simple virtual environment. We found no significant interaction effect between convergence ability and environment, $F(4, 90) = 1.17, p = .15$ and no significant effect of convergence abilities, $F(2, 45) = 2.67, p = .10$. We can thus assume that the stimulus size modulation was solely responsible for the difference we found between the simple virtual environment and the other two conditions.

Correlational analyses

Table 1 and Table 2 present the correlations between the different measures that we performed for the two distances separately and for the mean divergence and convergence scores, respectively. The first thing we notice is the correlation in vergence performance between real conditions with prism and the simple virtual environment, for divergence at 5 m and convergence at 40 cm and 5 m (respectively, $R = .44; p = .002; R = .44; p = .003; \text{ and } R = .41; p = 0.10$). Even though we found a correlation between the two virtual conditions for divergence and convergence at 40 cm ($p = .008$), there was no correlation between the complex virtual environment, i.e., the landscape, and the real environment (all $p > .05$). This first finding suggests that using landscape as a stimulus differs from using objects in terms of the processes that are mobilized to produce vergences. It also suggests that virtual reality permits the same types of measure as prisms in real conditions, provided that the stimuli are similar enough.

We also ran correlational analyses to examine the consistency between near and far vision. Concerning the convergence scores, we found correlations between the two distances for the three types of environments (all $p < .0001$). With regard to the divergence scores, we also found correlations between near and far vision for the simple virtual environment ($R = .64, p < .0001$) and the real environment ($R = .50, p < .0001$). The near vision divergence scores for the complex environment were not correlated with the 5-m divergence score, confirming that landscape as a stimulus differs from the other types of stimuli (isolated objects) ($p < .05$) and mobilizes different vergence modulation processes.

We examined the amplitude-of-fusion correlations between the different environments. Our findings are consistent with the analyses we ran on the separate vergence scores. Indeed, performances in a real environment were correlated with those obtained in the simple virtual environment for both distances (40 cm: $R = .44, p = .003$; and 5 m: $R = .36, p = .017$). We also found strong correlations between the two virtual environments for both distances (both $p < .0001$). The amplitude of fusion measured with the complex virtual environment was also correlated with the real environment at 40 cm ($R = .40, p = .007$) but not at 5 m ($R = .03, p = .83$). In conclusion, the use of virtual reality seems to provide similar measures of vergence as real conditions, especially for fusion amplitude.

Discussion

In this study, we examined the value of using virtual reality to measure vergence performances in adults. First, we hypothesized that virtual reality could provide similar measurements of vergence abilities as real conditions with prisms, while being more pleasant for the participants (Bryanton, Bosse, Brien, Mclean, McCormic, ..., & Sveistrup, 2006). Second, we hypothesized that by creating controlled environments, virtual reality techniques could make it possible to assess vergence more precisely. Finally, we thought that virtual environments with vast landscapes could help participants to relax their convergence systems compared to the real environment at a distance of 5 meters or the virtual environments with small objects.

With regard to the similarity of the vergence abilities across the environments, our results confirmed that virtual reality leads to measures very similar to those obtained in real conditions with prisms. Only divergence differed slightly in the virtual environment conditions. We observed poorer far vision performances with the Simple Virtual environment condition. We assume that this result is linked to a confounded effect of accommodation elicited by the reduction of the stimulus size as the distance to the object increased, a manipulation we introduced to induce the feeling of distance. Such a reduction in size might, unfortunately, have involuntarily induced accommodation, consequently bringing about convergence and reducing divergence performance. Indeed, it has been clearly shown that the accommodation system is highly sensitive to stimulus size (Kruger & Pola, 1985, 1986; McLin, Schor, & Kruger 1988). We found no such effect with the Complex Virtual environment, which yielded performances that were similar to those observed in real conditions. The fact that we did not obtain any comparable negative effect with the complex virtual environment could be due to the immersion effect produced by the background of the landscape. This would be consistent with the finding of Labhishetty, Cholewiak and Banks (2019), who showed that the stimuli that project out of the fovea to the peripheral retina play a role in regulating visual accommodation. This information from the peripheral visual field seems to help the brain interpret the size reduction as a distance cue and not as an accommodative need (Benel, 1979).

We hypothesized that complex environments could bring about high-level cognitive regulation due to the cognitive interpretation of contextual cues. Indeed, if vergence movements depend on a complex automatic regulatory process that is inaccessible to consciousness (Takagi, Oyamada & Abe, 2001) except in the case of voluntary convergence, then one question remains. This relates, for example, to the conflicts that might exist between the need for divergence and the need for accommodation through visual blur. Indeed, it is unclear whether there is a high-level regulatory process that modulates the vergence/accommodation ratio. It would be surprising if this oculomotor function were not regulated by such a process, as suggested by the results obtained by Esposito and Supèr (2019), which clearly showed an influence of cognitive functions on vergence performances. We therefore thought that a cognitive interpretation might modulate the amount of convergence that is activated or the extent to which convergence is relaxed and should lead to better performances in far divergence and worse performances in far convergence when a landscape is used as target. However, the performances observed in our study were similar in the real conditions and in the Complex Virtual conditions with the landscape. Consequently, the present findings suggest that only low-level regulatory processes were involved during our task, especially with regard to the size of the stimulus projection onto the fovea and the low-level interpretation of the information from the background of the scene through the peripheral retinal cells. This observation is consistent with the work of Lang and colleagues (Lang, Gaertner, Ghassemi, Yang, ..., & Kapoula, 2014) who found that repeated movements were more effective in improving vergence than temporal gap. Indeed, repetition may give rise to automatization, whereas “gap” suggests control by a high-level process.

However, the correlational analyses suggest that even if the complex virtual environments did yield measures similar to those obtained under real conditions, different types of processes were mobilized by the complex landscape projected in the headset. Indeed, the measures were not correlated with those obtained for the other two environments. This suggests that the processing of background information does indeed play an important role in regulating the convergence-accommodation system. Nevertheless, other studies will be needed in order to clarify the influence of high-level processes on the control of vergences.

As a conclusion, our results confirm that measuring vergences using virtual reality equipment is similar to measuring them in real conditions with prisms. Our results thus emphasize that it is more important to control for the perceptual characteristics of the stimuli than for the cognitive context, at least when simulating vergence in a virtual reality setting. These results also highlight that even if the visual information from the scene is processed automatically, the quality of the information from the background clearly plays a role in determining the quality of vergence stimulation (Levi, 2023).

If we now consider the fusion performance, which is more relevant for evaluating the integrity of disjunctive ocular movements (Kapoula, Morize, Daniel, Jonqua, ..., & Bremond-Gignac, 2016), we obtained better fusion in both the virtual reality environments than in the real environment, a finding which is consistent with our hypothesis. This suggests that the virtual environments provided even better conditions for measuring vergences than the real environment. One explanation of this superiority of virtual reality over real conditions could be linked to bottom-up attentional processes. Indeed, even when participants fixate the stimulus in a real environment, they are nevertheless continuously exposed to many variations in the visual inputs, e.g. the movements of the physician as he or she moves the prisms for the measurement. Even if the participants remain attentive to the task, their retinal receptive fields involuntarily process the movements at both a local and a high level and their attention is automatically attracted toward the external movements (Awh, Belopolsky & Theeuwes, 2012; Connor, Egeth & Yantis, 2004). We suggest that the need to inhibit saccadic eye movements directed toward the external

movements could interfere with performance in the vergence task (Findlay & Walker, 1999; Takagi, Oyamada & Abe, 2001). Furthermore, even if large saccadic movements are inhibited, some small saccades could still occur and disrupt fusion (Coubard & Kapoula, 2008). Indeed, it is well known that fusion is disrupted during saccadic movements, such as those that occur during visual perception (Schütz, Braun & Gegenfurtner, 2011). Little is known about the role of attentional focus in vergence performance but it is possible that distractors might also have an impact on performances (Hoffman, 2016; Remington, 1980). Future studies will be needed to clarify the role of automatic and cognitive attention in vergence ability and to examine whether the fusion is altered by micro-saccades during vergence measurements in real conditions with prisms.

Finally, we found no major effect of convergence relaxation in the virtual reality environments, except in the case of the participants with strong convergence. It appears that the quality of the stimulation enhanced the participants' divergence performances, which are probably underestimated in real conditions. We suggest that the very gradual movement produced by the VR device and the symmetry of the stimulation – with both eyes moving together with the headset, whereas the prism is placed on one eye only - had a beneficial effect on the quality of divergence stimulation compared to real conditions. However, the participants in our study exhibited no accommodation problems. It could be useful in the future to test such simulations with patients who have specific difficulties in relaxing their accommodation.

Conclusion

Our study showed that virtual reality provides a good way to measure vergence abilities and produces results very similar to those obtained in real conditions. This method might even be a better way of evaluating vergences as it offers a more controlled environment. It could be particularly helpful when assessing patients with attention disorders. It will be necessary in the future to conduct clinical trials with participants with vergence disorders and to evaluate the efficacy of such solutions for vergence reeducation. Finally, this type of mechanism will also be helpful for understanding the regulatory processes involved in ocular movements, especially with regard to the dynamic aspects of oculomotricity in three-dimensional space.

Acknowledgments

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