Investigating Cyclical Stereoscopy Effects over Visual Discomfort and Fatigue in Virtual Reality while Learning

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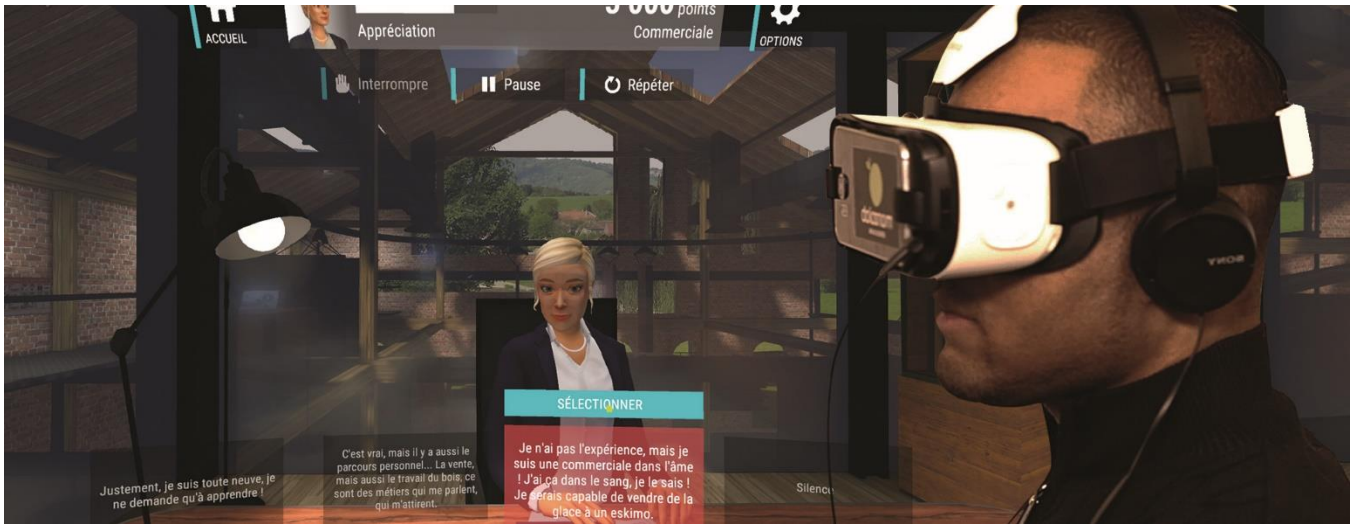


Fig. 1. Serious Game in front of the recruiter (left) Subject wearing a Samsung Gear VR (right) © Manzalab

ABSTRACT

Purpose: It is hypothesized that cyclical stereoscopy (displaying stereoscopy or 2D cyclically) has effect over visual fatigue, learning curves and quality of experience, and that those effects are different from regular stereoscopy. Materials and Methods: 59 participants played a serious game simulating a job interview with a Samsung Gear VR Head Mounted Display (HMD). Participants were randomly assigned to 3 groups: HMD with regular stereoscopy (S3D) and HMD with cyclical stereoscopy (cycles of 1 or 3 minutes). Participants played the game thrice (third try on a PC one month later). Visual discomfort, Flow, Presence, were measured with questionnaires. Visual Fatigue was assessed pre- and post-exposure with optometric measures. Learning traces were obtained in-game. Results: Visual discomfort and flow are lower with cyclical-S3D than S3D but not Presence. Cyclical stereoscopy every 1 minute is more tiring than stereoscopy. Cyclical stereoscopy every 3 minutes tends to be more tiring than stereoscopy. Cyclical stereoscopy groups improved during Short-Term Learning. None of the statistical tests showed a difference between groups in either Short-Term Learning or Long-Term Learning curves. Conclusion: cyclical stereoscopy displayed cyclically had a positive impact on Visual Comfort and Flow, but not Presence. It affects oculomotor functions in a HMD while learning with a serious game with low disparities and easy visual tasks. Other visual tasks should be tested, and eye-tracking should be considered to assess visual fatigue during exposure. Results in ecological conditions seem to support models suggesting that activating cyclically stereopsis in a HMD is more tiring than maintaining it.

Keywords: virtual reality, serious game, visual fatigue, head-mounted display, cyclical stereoscopy.

Index Terms: [Computing methodologies]: Virtual reality—Perception; [Software and its engineering]: Interactive games

1 INTRODUCTION

Virtual Reality Head-Mounted displays (HMDs) have impacts on the human visual system (HVS), i.e. visual fatigue, especially due to displayed imaging [1]. Displaying stereoscopy (S3D) imaging can lead to Visual Fatigue and discomfort [2] due to vergence-accommodation conflicts [3]. Previous works with consumer HMDs has been conducted about Visual Fatigue and learning showing needs for limiting [4] visual stress.

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Accommodation-Vergence conflict seems to be linked with cognitive load [5]. Therefore, such conflicts could affect learning efficiency. Even though, based on Hirota *et al.* results, new consumer HMDs could lead to visual fatigue with little difference between biocular (the same image without disparity displayed on both screens of the HMD) and stereoscopic imaging (two images with a parallax displayed on each screen, providing depth cues when fusing them) stimuli [6]. Their results are obtained with stereoscopic stimuli with a parallax < 1°. Techniques proposals and empirical evidences are needed to reduce visual fatigue [7]. Prior to reducing visual fatigue, it appears to us that documenting cyclical stereoscopy effects is needed.

The present paper proposes an experiment to test feasibility and effects of cyclical stereoscopy in a VR-HMD over the visual system while learning, since learning has a higher requirement of working memory resources.

2 Related Works

2.1 Visual fatigue in HMDs and with S3D

Previous works have been documenting effects of both HMDs and S3D over human visual system [8]-[11]. They pointed out that stereoscopic imaging decorrelates the vergence-accommodation processes [12], [13]. This conflict between vergence and accommodation and physiological changes due to stereoscopy, leading to visual fatigue seems to be the consensus and remain observed in presently studies [14], also with Augmented Reality devices [3]. The two processes, within a HMD displaying stereoscopic imaging are occurring on different planes [15, p. 70].

From this perspective it will be necessary to better understand the seemingly contradictory results of Cai *et al.* and Chen *et al.* or to present ecological evidence for one or another. The study by Cai *et al.* suggests that the process of activating stereopsis is more tiring than its sustaining process [16]. This implies that cyclical S3D would prove equally tiring, if not more than permanent stereoscopy. The study by Chen *et al.* indicates, on the contrary, that fatigue is linked to the maintenance of stereopsis [17]. This implies that cyclical stereoscopy would be less tiring than continuous stereoscopy. Contradictions in proposed models motivate to focus on empirical proofs without particular "pre-accession."

2.2 Intermittent or Cyclical Stereoscopy and visual fatigue

2.2.1 Cyclical Stereoscopy

Cyclical stereoscopy has been studied by some authors for its ability to relax vergence and possibly reducing visual fatigue [18]. Most researches consist in using intermittent stereoscopy to reduce visual fatigue and/or discomfort. Bando *et al.* list three approaches to prevent eye fatigue: aligning images with eyes, limiting disparity, controlling viewing conditions (viewing distance, camera position) [19]. Although the contribution of Bando *et al.* integrates HMDs, most of the recommendations to reduce the visual stress remain very general and are partly relevant to the contents in our case. As noted by Terzić and Hansard through their review, methods for reducing visual discomfort or fatigue are varied [20]. They indicate that these methods are hardly comparable because they include different variables. In addition, some algorithms are general in their content processing, i.e. affecting broadly stimuli without personalisation or very specific to a content, thus not considering the many differences between people.

We identify two types of reduction: active and passive. An active reduction consists of implementing computer modules applying corrections to the software or the hardware dynamically (e.g. reduction of spatial frequencies or blur in unseen locations). A passive reduction consists of adjusting the properties of the content during the design in order to minimize the visual stress, in a non-dynamic way (e.g. not exceeding a certain disparity, excluding the images with high spatial frequencies). Here we concentrate on an active reduction: intermittent and cyclical stereoscopy and researches using it for reducing visual fatigue. Evolutions from HMD engineering (e.g. lens adaptation following accommodation or screen technologies) are not tackled in the following literature review as they are not currently used in consumer technologies, yet are very promising. Work for reducing visual fatigue has been identified to be necessary [4]. This is our base in order to tackle effects of cyclical stereoscopy over visual discomfort and fatigue.

2.2.2 Intermittent stereoscopy

Using stereoscopy intermittently to display depth takes advantage of stereoscopy's usefulness on spatialization, for example. This idea was proposed by Matsuura in 2013 [21]. According to his study, the subjective rating of subjects indicates a decrease in visual fatigue. In addition, Matsuura reports that subjects maintain their depth perception of objects presented even when they are no longer stereoscopic. As a result of this work, Bouaniche and Leroy evaluated this approach in the context of specific tasks. They offered four tasks to subjects (N = 60) and measured completion based on four conditions [22]. Subjects must discriminate depth in a Virtual Environment (EV). Two of these conditions consist of proposing stereoscopy at the beginning of the task and then at the end of the task with a return to binocularity (i.e. the same image displayed on both screens, without parallax) within three seconds. The other two are control conditions: stereoscopy and biocular imaging. Their results suggest a correlation between visual fatigue and stereoscopic exposure time. However, the observed differences are not significant which echoes with contradictions in models explaining visual fatigue mechanisms highlighted in the previous section. They also report a correlation between performance and stereoscopy. They observe that stereoscopy at the beginning appears more efficient for the task's fulfilment than stereoscopy at the end. However, visual fatigue of stereoscopy at the beginning is more tiring than stereoscopy at the end. Bouaniche and Leroy assert that subjects' depth perception is maintained and forms a "depth map" in the brain [23]. However, this effectiveness is variable according to the tasks. Guo *et al.* had subjects playing a game in VR with a HMD and resting for 3 minutes every 20 minutes [24]. This strategy is a passive reduction of visual fatigue but since it as cyclically approach, this study is worth noting. Resting has positive effects on relaxing the visual system although subjects subjectively declared more discomfort while doing breaks during the game.

2.2.3 Considering effects of cyclical stereoscopy on the human visual system

Cyclical stereoscopy has been studied in order to reduce visual fatigue through several conditions specific to Serious Game combined with VR. Review of Terzić and Hansard illustrates a lack of literature on HMDs and Serious Games (SG) [20] for reducing visual fatigue. Many of the solutions proposed by the previous contributions concentrate globally on static images or videos. If they are Virtual Environments, they are simple, with a low aesthetic at stake and rarely involving learning. In our context, the technique involves: 1) selecting simple solutions to implement, 2) not requiring a lot of computing resources from the device, 3) guaranteeing limited visual stress, 4) solution agnostic to proposed interactions, therefore flexible and adaptable to most HMDs.

Therefore, cyclical stereoscopy seems interesting to explor as it avoids complex computing. The study of Bouaniche and Leroy draws possibilities involving further investigations in an ecological context [22]. Their study, like Matsuura's one, suggests that the human brain would keep depth information in memory even when it is no longer

perceived by the visual system [21]. Disparity can be changed during viewing [25]. Providing stereoscopy at the precise moment, or just before, when discrimination of distance, depth, are necessary could allow to benefit of the interest of stereoscopy. It is still unknown if returning to biocularity could limit visual stress. However, such cues seem especially necessary in order to act with a close object with ones hands [26]. In addition, as showed by Kulshreshth and LaViola, intermittent stereoscopy can be dynamically managed [27]. Koulieris *et al.* suggest that a more comfortable vision of their subjects also comes with a sense of good depth perception [28]. Design practices, such as the one provided by Porcino *et al.*, from the compilation of some of these studies with HMDs, are beginning to formalize to reduce discomfort in general [29]. However, they rely on subjective questionnaire only and other empirical evidence is lacking. Cyclical stereoscopy might allow to retain the advantage of depth information but it remains unsure if it could reduce visual stress in a learning context. In addition, some Serious Games, depending on the tasks to be performed may not require stereoscopy at all. Allowing biocular imaging would relax vergence and alleviate conflict with accommodation during exposure.

2.3 Experiment

Except for Matsuura [21] and Bouaniche and Leroy [22] studies, intermittent and cyclical stereoscopy remains little investigated. Their investigations have been conducted with Virtual Environments with weak aesthetic issues, cognitive load and interactions. Their experimental conditions do not mobilize HMDs. Therefore, it would be relevant to evaluate stereoscopy use before a task of depth discrimination and / or only when carrying out such tasks. It could also be relevant when depth discrimination is not determining for the task completion (in our case learning) in order to validate early results with easy visual tasks in ecological conditions. This is the last configuration that this study proposes to tackle. Since studies are still very heterogeneous, our primary purpose is to measure effects of cyclical stereoscopy over the visual system through the assessment of visual discomfort and fatigue. Our second purpose is to assess its efficiency at reducing discomfort and fatigue. This experiment is operated in a learning context. First, for its higher cognitive load than previous studies, as cognitive load and accommodative-vergence seems linked [5] as well as visual fatigue and cognitive fatigue [30]. Second, for its ecological validity as previous works are usually fundamental, using psychophysical tests or alike. HMDs are already used by professionals with learning contents without a clear view of human factors' limits (i.e. visual fatigue) [7].

3 Material and Methods

This study proposes to expose subjects to a serious game in virtual reality by varying imaging (stereoscopy or cyclical stereoscopy). The subjects are randomly divided into 3 groups:

- Group A, binocular imaging (HMD-S3D)
- Group B, cyclical binocular imaging every 1 minute (HMD-S3D-1c)
- Group C, cyclical binocular imaging every 3 minutes (HMD-S3D-3c).

Stereoscopy settings are based on Oculus recommendations and all groups were using a Samsung Gear VR with a Galaxy S6. Stereoscopy is applied on each object including texts. The steps of this protocol are performed in accordance with the methodology of simple-blinded investigation and between-subject design.

3.1 Ethical aspects and recruitment

The subjects were volunteers. This research protocol has been reviewed and approved by the CER – Paris Descartes, registered as: 2018 – 51. This study has been declared to the CNIL (National Commission on Informatics and Liberty) relating to data collection and protection registered which validated conformity with the "MR1 - Health research with consent" methodology, registered as: 2120463 v 0. An information letter indicated the aims of the study to the volunteers and a consent form was signed by the subjects before starting the experiment. Recruitment was done online via social networks and a mailing list (RISC by the CNRS). A € 20 voucher compensation for each subject was given.

3.2 Serious Game in VR used

This serious game aims to train people for a job interview (Fig. 1). The learning instructions have been built based on the confidential standards of Human Resources of Pôle Emploi (French governmental agency: employment centre). A unique scenario based on a salesperson position is used for each group and each try. The game's goal is to choose the most relevant answer.

Subjects choose an avatar between a male and a female corresponding to their gender, then take notice of the job offer and the resume of the avatar. Then, the scenario consists of 1) Discussion with a friend (male or female according to the subject's choice of avatar: if male is chosen by subject then the friend is a female and inversely) to prepare for the interview, 2) Reading the company's website, 3) Interview with the recruiter, 4) Review of the interview with a coach. Answers are selected by placing a green dot over the chosen answer between three to four possibilities. Dialog voices (friend and recruiter) have been registered with professional actors. The player can turn the camera 360°. Subjects have a first-person viewpoint and cannot see their avatar.

Each answer gives points according to the relevance to the question asked, the context, and the standard codes of job interview. A score is displayed in real time and changes according to the player's choices. A loading bar symbolizes the time remaining for answering. A feedback is given after answering red = unsuitable, orange = average, green = expected. In the third act, the coach comments the strengths and weaknesses of the player during the interview. The final score is displayed and a percentage of achievement in the three skills is listed: marketing = ability to "sell oneself," communication = ability to communicate according to expected codes, conduct = ability to lead the interview. This allows the learner to identify possible improvements.

3.3 Apparatus

3.3.1 Samsung Gear VR™ characteristics

Model: SM-R321; This HMD requires a smartphone inserted. Its technical characteristics are as follows: Field of View: 90°; tracking: 3 Degree of Freedom with Accelerometer and Gyroscope in the Galaxy S6; weight: 345 grams.

3.3.2 Samsung© Galaxy 6™ characteristics

OS: Android 8.1; Processor: Samsung Exynos 7 Octa @ 2,1 GHz; graphic card: ARM Mali T760; memory: 3 GB (RAM); display: 5.1" Quad HD Super AMOLED. 2560 x 1440 px (577 ppi); luminance: 432 cd/m^2.

3.3.3 Headphones Sony©

Model: MDR-ZX110B. Frequency: 12 to 22 kHz; diaphragm: 30 millimeters; weight: 120 grams.

3.4 Cyclical stereoscopic setting

Cyclical stereoscopy aims at relaxing vergence, therefore allowing the visual system to perform it closer to the accommodation plane. Previous work by Emoto *et al.* about oscillation of disparity for stereoscopic TV showed that subjects can perceive even very fast changes [13]. Their changing cycles were every 5 seconds. Therefore, maintaining disparity state for 5 seconds.

We conducted pre-tests with N = 10 subjects that weren't included in the rest of the study in order to validate cyclical stereoscopy displaying timing and cycles (*t* and *d* in our equation). The aim was to make sure subjects couldn't perceive the imaging change. To switch from bi-ocular to stereoscopy with Unity 3D, we simply programmed a loop to switch from state to another. The switch occurs at each frame to gradually change the scale of the object that contains the camera.

With Unity 3D we use the Mathf.Lerp function[1]. The scales of the cameras are dynamically changing. Scale = 1 equals the parallax setting based on oculus recommendation. Scale ~ 0 correspond to the two cameras with no parallax. The interpolation is linear from start (stereoscopy) to the reach scale (bi-ocular):

$$(s_{max} - s_{min}) * \frac{t}{d} + s_{min}$$

s_{min} = Starting Scale, s_{max} = Reach Scale, t = Time spent since the beginning of a loop, d = Duration of the loop.

Following pre-tests, duration and timing have been set as follow:

- t = 22 seconds
- d = 5 seconds.

The linear interpolation of 22 seconds has not been detected by the 10 subjects from the pre-tests which guided this choice of timing. The 5 seconds of duration have been set based on previous work by Emoto *et al.* and Ware in order to make sure that subjects would not perceive changes in imaging as it could impact their Quality of Experience [13], [25]. The loop changing imaging and maintaining state takes 49 seconds. We give 11 seconds for the visual system to rest as Emoto *et al.* showed that changes that are too quick can be detected by humans. We doubled their 5 seconds maintaining state after changing imaging and added 1 second to round cycles. This makes 1 minute. For the 3 minutes, we considered the 3 minutes rest used by Guo *et al.* which appeared efficient every 20 minutes [24].

3.5 Participants

59 subjects took part in this study. The sample consisted of 31 women and 28 men aged 18 to 38, M = 23.81 ± 0.64 (SD = 4.84) years. Subjects were excluded if: over the age of 40 (presbyopia can influence optometric tests assessing accommodation), declaring a pathology greatly influencing the state of the visual system and perceptions. The subjects were mainly students (mainly digital, computer sciences and psychology). Half of participants were looking for an internship during the experiment. 24 subjects had no correction and 35 had either glasses or correction lenses (*see Tab. 1*).

Tab. 1: Visual default repartition by group

	Group			n
	A	B	C	
Myopia	6	5	6	17
Astigmatism	1	0	0	1
Myopia + Astigmatism	0	4	2	6
Hyperopia	1	1	2	4
Hyperopia + Astigmatism	3	0	2	5
Strabismus	0	0	1	1
Fatigue	0	1	0	1
Sum	**11**	**11**	**13**	**35**

Only part of the initial subjects took part for Long-term Learning assesment, other desengaged of the study as this is their right.

[1] Unity - Scripting API: Mathf.Lerp. *Docs.unity3d.com*, 2018 [online]. Available at: https://docs.unity3d.com/ScriptReference/Mathf.Lerp.html [Accessed 29 Nov. 2018].

3.6 Procedure and measures

The procedure was divided into two stages, one month apart. Prior to the first stage of the study, subjects completed a profile questionnaire. Subjects signed the consent form after receiving the information about the study at the beginning of the first stage.

1) Visual Fatigue is assessed through optometric measurements performed before (pre-) and after (post-) exposure at 40 cm from the subject with a head-chin rest (Punctum proximum of accommodation and stereoscopic acuity) and with the Smartoptometry© application on a Samsung Galaxy tablet (ease of accommodation and visual acuity):

- Punctum proximum of accommodation, measured with the Donder's Push-up Test, then clustered at a speed of 5 to 7.5 cm per second,
- Stereoscopic acuity, measured with the TNO test,
- Ease of accommodation, measured via the Flipper lens test (+2.00 / -2.00) for 1 minute with the Smartoptometry© feature displaying words on a tablet that participants had to swipe when seen in-focus,
- Visual acuity measured by detecting the E of Raskin (random) orientation of smaller and smaller dimensions.

2) Subjects receive explanations of the game's purposes and interactions then are helped to get equipped by following a rigorously similar script for each condition, not making variations in instructions. Subjects are exposed for M = 34.20 minutes, (SD = 3.94). This corresponds to first and second try in a row, without break, for the three groups. Exposure time includes reading, dialogues and Response Time in the Serious Game. 30 minutes is a reference time in the literature [31]. Subjects sit on a chair during exposure and play two games (G1 and G2) of the SG. Learning curves are assessed via data collected during the game: scores and response time as markers of memorization. Low values of In-Game Score correspond to low learning performance and low Response Time correspond to high learning performance.

3) The quality of experience is assessed via questionnaires with Likert scales graduated from 1 to 5 (translated in French by the first author):

- Visual discomfort: measured via the questionnaire by Zeri and Livi consisting in 11 items [32],
- Presence: measured via the Multimodal Presence Scale by Makransky *et al.* with the spatial and social presence items being 10 items because the self-presence part is not relevant since subjects don't have to move their body and cannot see their avatar [33],
- Flow: measured via the Flow Short Scale by Rheinberg, Vollmeyer and Engeser consisting in 9 items [34].

4) The Tinetti-Poma test was performed to ensure subjects were able to walk out of the building with perfect balance reflexes.

During the second stage, 4 weeks after the first stage, participants of the 3 groups played at home the exact same Serious Game and scenario, on their own PC (G3). This unique try lasted about 15 minutes. Data are sent to the first author.

3.7 Analysis and statistics

The random assignation resulted in: group A, 20 subjects; group B, 19 subjects; group C, 20 subjects. Tests are carried out on one hand in each group and on the other hand between groups. The significance level is

tested with a confidence of $\alpha = 0.05$. Jamovi version 0.9.5.12 (2018) was used for statistical tests. Shapiro-Wilk tests were performed to test the distribution for each set of data and determine the appropriate tests to perform.

3.8 Hypotheses

H1: optometric variables are different between pre- and post-measurements after exposition to cyclical-S3D in a SG via VR-HMD

H2: S3D leads to a higher visual fatigue than cyclical-S3D in a SG via VR-HMD

H2b: cyclical-S3D for 1 minute leads to a higher visual fatigue than cyclical-S3D for 3 minutes in a SG via VR-HMD

H3: learning is improving between first and second try with cyclical-S3D in a SG via VR-HMD

H4: learning curves are higher with cyclical-S3D than S3D in a SG via VR-HMD

H5: quality of experience is higher with cyclical-S3D than S3D in a SG via VR-HMD

4 Results

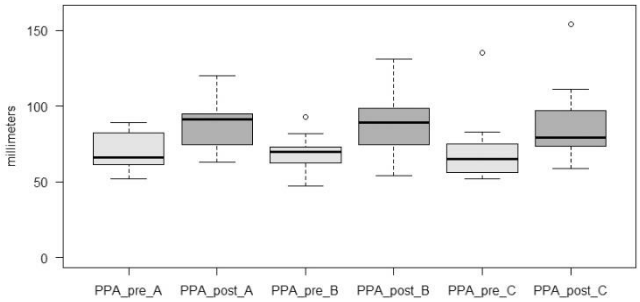


Fig. 2. Punctum Proximum of accommodation pre- and post-exposure by group in millimeters (the higher the measure, the higher the Visual Fatigue). Group A: S3D, Group B: S3D-1c, Group C: S3D-3c

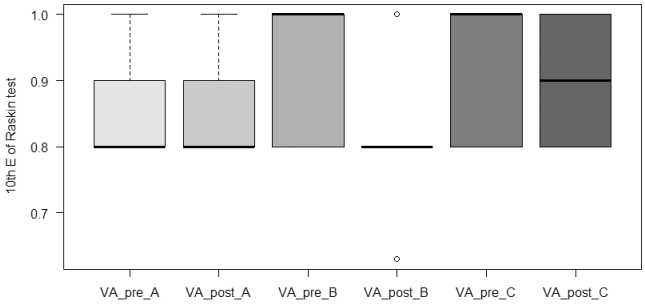


Fig. 3. Visual Acuity pre- and post-exposure by group in Scores at the E of Raskin Test. Group A: S3D, Group B: S3D-1c, Group C: S3D-3c

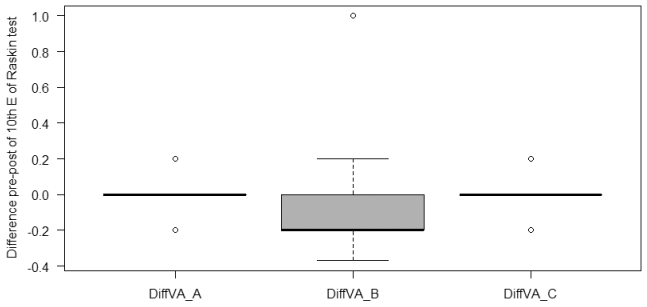


Fig. 4. Visual Acuity pre- and post-exposure between group Scores at the E of Raskin Test. Group A: S3D, Group B: S3D-1c, Group C: S3D-3c

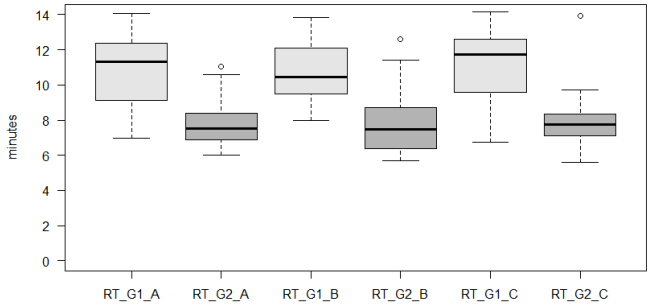


Fig. 4. Response Time by group for each game in minutes. Group A: S3D, Group B: S3D-1c, Group C: S3D-3c (Game1 lighter grey; Game2 grey)

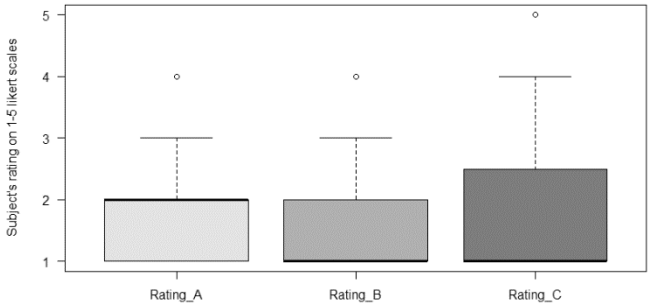


Fig. 5. Visual discomfort by group after the two tries. Group A: S3D, Group B: S3D-1c, Group C: S3D-3c

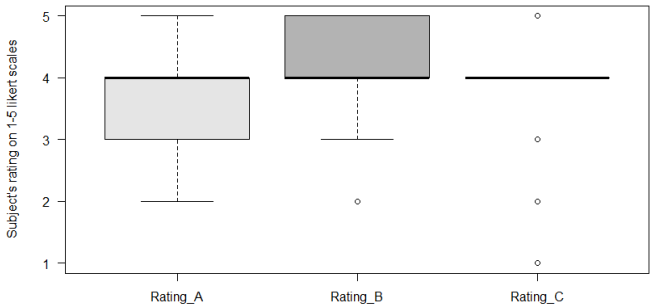


Fig. 6. Flow by group after the two tries. Group A: S3D, Group B: S3D-1c, Group C: S3D-3c

4.1 Visual Fatigue

See Tab. 2. Visual Fatigue Results

Tab. 2: Statistical tests Results Visual Fatigue

Metric	Condition	Tested	Statistical test	M_{pre}	SD_{pre}	M_{post}	SD_{post}	MD	Result	Significant	%*
PPA (a)	Group A	pre- ≠ post-exposure	t-test	69.40	12.27	87.00	14.72		t (20) = -9.17, **p = < .001**	**yes**	
PPA (a)	Group B	pre- ≠ post-exposure	t-test	67.37	11.40	87.37	18.95		t (19) = -7.60, **p = < .001**	**yes**	
PPA (a)	Group C	pre- ≠ post-exposure	Wilcoxon Sign Rank					-18.5	Z = -3.92, **p = < .001**	**yes**	
ΔPPA (b)	Between Groups	Groups are ≠	ANOVA						[F(2) = 0.25, p = .77]	no	
EoA (c)	Group A	pre- ≠ post-exposure	t-test	31.1	11.45	32.2	11.83		t (19) = -1.13, p = .27	no	-1.58%
EoA (c)	Group B	pre- ≠ post-exposure	t-test	33.3	13.41	32.3	10.96		t (18) = 0.78, p = .45	no	+7.45%
EoA (c)	Group C	pre- ≠ post-exposure	t-test	34.6	8.84	34.2	9.08		t (19) = 0.32, p = .55	no	-10.38%
ΔEoA (d)	Between Groups	Groups are ≠	Kruskal-Wallis						(H(0.92 = 2, p = .63)	no	
VA (e)	Group A	pre- ≠ post-exposure	Wilcoxon Sign Rank					0	Z = 0, p = .00	no	0%
VA (e)	Group B	pre- ≠ post-exposure	Wilcoxon Sign Rank					0.20	Z = -2.45, **p = .01**	**yes**	-90.91%
VA (e)	Group C	pre- ≠ post-exposure	Wilcoxon Sign Rank					0.01	Z = -0.73, p = .48	no	-16.67%
ΔVA (f)	Between Groups	Groups are ≠	Kruskal-Wallis						(H(6.52 = 2, **p = .04**)	**yes**	
SA (g)	Group A	pre- ≠ post-exposure	Wilcoxon Sign Rank	5.45	1.43	5.20	1.74		Z = -0.87, p = .38	no	-4.59%
SA (g)	Group B	pre- ≠ post-exposure	Wilcoxon Sign Rank	5.00	1.60	5.11	1.73		Z = -0.56, p = .61	no	+2.11%
SA (g)	Group C	pre- ≠ post-exposure	Wilcoxon Sign Rank	5.15	2.16	5.05	2.28		Z = -0.59, p = .59	no	-1.94%
ΔSA (h)	Between Groups	Groups are ≠	Kruskal-Wallis						(H(1.75 = 2, p = .42)	no	

(a) PPA: *Punctum Proximum of Accommodation*. The higher the Donder's Push-up Test score, the lower is the PPA. **(b)** In order to test the between groups' data, we subtracted the scores pre- and post-exposure, which gives us a ΔPPA value. Data are in millimeter. **(c)** EoA: *Ease of Accommodation*. The lower the Flipper lens test's score, the lower the EoA. Data are in number of half-cycles registered for 1 minute. **(d)** In order to test the between groups' data, we subtracted the scores pre- and post-exposure, which gives us a ΔEoA value. **(e)** VA: *Visual Acuity*. The lower the test's score, the lower the visual acuity. Data are in tenth based on usually used scale by orthoptists. **(f)** In order to test the between groups' data, we subtracted the scores pre- and post-exposure, which gives us a ΔVA value. **(g)** SA: *Stereoscopic Acuity*. The lower the TNO test score, the lower the stereoscopic acuity. **(h)** In order to test the between groups' data, we subtracted the scores pre- and post-exposure which gives us a ΔSA value.

* percentage of difference between pre- and post-exposure measures

4.1.1 Punctum Proximum of Accommodation (PPA)

PPA of groups A, B and C significantly increases between pre- and post-exposure, revealing a negative impact of exposure for each displayed imaging (*Fig. 2*).

ΔPPA between groups A, B and C did not vary differently which indicates inefficiency of cyclical stereoscopy at reducing visual fatigue based on that optometric variable.

4.1.2 Ease of accommodation (EoA)

EoA differences between or within groups were not statistically significant. The medians' tendency indicates that condition B was the less tiring followed by condition C and finally condition A.

4.1.3 Visual acuity (VA)

VA difference between pre- and post-exposure for groups A and C were not significant (*Fig. 3*). For group B that the median pre-exposure ranks, MD = 0.03, was statistically different from the median post-exposure ranks Z = -2.45, **p = 0.01**.

The **Kruskal-Wallis Test indicated that there was a significant difference in visual acuity pre- and post-exposure difference (ΔVA) between groups** (H(6.52 = 2, **p = 0.04**) with a mean rank of 34.75 for group A, 23.05 for group B and 31.85 for group C. Dwass-Steel-Critchlow-Fligner pairwise comparison Post-Hoc tests showed a significant difference between groups A and B (MD = 0.11, SE = 0.04) W = -3.45, **p = .015**. No difference between other groups were found with Post-Hoc tests (*Fig. 4*).

Based on visual acuity, cyclical stereoscopy with 1 minute (group B) cycles seems more tiring than regular stereoscopy (group A).

4.1.4 Stereoscopic acuity (SA)

SA differences between or within groups were not statistically significant. The medians' tendency indicates that condition A decreased the most followed by group C while group B increases score at the Stereoscopic acuity test between pre- and post-exposure.

4.1.5 Visual Fatigue results' Summary

Only Punctum Proximum of Accommodation and Visual Acuity varied significantly. While comparing groups, Visual Acuity showed a negative impact of 1 minute cycle stereoscopy (group B). These results support only poorly H1 stating that optometric variables are different between pre- and post- measurements after exposition to cyclical-S3D in a SG via VR-HMD. It doesn't support H2 stating that S3D leads to a higher visual fatigue than cyclical-S3D in a SG via VR-HMD, nor H2b stating that cyclical-S3D for 1 minute leads to a higher visual fatigue than cyclical-S3D for 3 minutes in a SG via VR-HMD (see Tab. 2).

Tab. 3: Statistical tests Results Short Term Learning

Metric	Condition	Tested	Statistical test	M_{G1}	SD_{G1}	M_{G2}	SD_{G2}	MD	Result	Significant	%* / mn**
IGS G2-G1 (i)	Group A	G2 ≠ G1	Wilcoxon Sign Rank					-8000	Z = 9.50, **p = < .001**	**yes**	+20.95%
IGS G2-G1 (i)	Group B	G2 ≠ G1	Wilcoxon Sign Rank					-9500	Z = 32.00, **p = .01**	**yes**	+18.10%
IGS G2-G1 (i)	Group C	G2 ≠ G1	Wilcoxon Sign Rank					-9000	Z = 16.50, **p = .001**	**yes**	+19.10
IGS ΔG2-G1 (j)	Between Groups	Groups are ≠	Kruskal-Wallis						(H(0.55 = 2, p = .76)	no	
RT G2-G1 (k)	Group A	G2 ≠ G1	Wilcoxon Sign Rank					4.27	Z = -3.92, **p = < .001**	**yes**	2.88 mn
RT G2-G1 (k)	Group B	G2 ≠ G1	t-test	10.69	1.84	7.92	1.88		t (11) = 5.96, **p = < .001**	**yes**	2.77 mn
RT G2-G1 (k)	Group C	G2 ≠ G1	Wilcoxon Sign Rank					1.83	Z = -3.30, **p = < .001**	**yes**	3.32 mn
ΔRT G2-G1 (l)	Between Groups	Groups are ≠	ANOVA						[F(2,56) = 0.45, p = .64]	no	

(i) *IGS: In-Game Scores*. The higher the in-game score, the higher the learning (memorization). Data corresponds to the In-Game Score ranging from 0 to 63000. **(j)** In order to test the between groups' data, we subtracted the in-game scores G2 and G1 which give us a ΔG2-G1 value for learning evolution from first to second try. **(k)** *RT: Response Time*. The higher the Response Time, the lower the learning. Data are in minutes. **(l)** In order to test the between groups' data, we subtracted the Response Time for G2 and G1 which give us a ΔRTG2-G1 value.
* percentage of difference between G1 and G2 In-Game Scores
** Response Time difference between G1 and G2 in minutes

Tab. 4: Statistical tests Results Long Term Learning

Metric	Condition	Tested	Statistical test	M_{G2}	SD_{G2}	M_{G3}	SD_{G3}	MD	Result	Significant	%* / mn**
IGS G3-G2 (m)	Group A	G3 ≠ G2	t-test	44737	9590.79	40684	6382.98		t (18) = 2.23, **p = .04**	**yes**	-12.16%
IGS G3-G2 (m)	Group B	G3 ≠ G2	Wilcoxon Sign Rank					15812.50	Z = -0.41, p = .75	no	-0.25%
IGS G3-G2 (m)	Group C	G3 ≠ G2	t-test	52929	5174.99	44857	8475.65		t (13) = 3.52, **p = .002**	**yes**	-14.94%
IGS ΔG3-G2 (n)	Between Groups	Groups are ≠	ANOVA						[F(2) = 29.2, p = .09]	no	
RT G3-G2 (o)	Group A	G3 ≠ G2	t-test	7.73	1.18	6.86	1.41		t (18) = 2.53, **p = .02**	yes	0.87 mn
RT G3-G2 (o)	Group B	G3 ≠ G2	Wilcoxon Sign Rank					-0.31	Z = -0.72, p = .49	no	0.37 mn
RT G3-G2 (o)	Group C	G3 ≠ G2	t-test					2.5	Z = -1.98, **p = .05**	yes	0.99 mn
ΔRT G3-G2 (p)	Between Groups	Groups are ≠	ANOVA						[F(2) = 28.3, p = .57]	no	

(m) *IGS: In-Game Scores*. The higher the in-game score, the higher the learning (memorization). Data corresponds to the In-Game Score ranging from 0 to 63000. **(n)** In order to test the between groups' data, we subtracted the in-game scores G3 and G2 which give us a ΔG3-G2 value for learning evolution from first to second try. **(o)** *RT: Response Time*. The higher the Response Time, the lower the learning. Data are in minutes. **(p)** In order to test the between groups' data, we subtracted the Response Time for G3 and G2 which give us a ΔRTG3-G2 value.
* percentage of difference between G2 and G3 In-Game Scores
** Response Time difference between G2 and G3 in minutes

4.2.1 Short Term Learning (comparison G1-G2)

See tab. 3.

In-Game Score (IGS): there are statistical differences between the first try (G1) and the second try (G2) within each group. All groups improved between their first and second try.

Response Time (RT): Subjects' Response Time is shorter during G2 compared to G1 for the three conditions (*Fig. 5*).

4.2.2 Long Term Learning (comparison G2-G3)

See tab. 4.

49 subjects took part to the second stage of the study within the 59 from the first stage. 11 subjects choose, as this is their right, not to participate further. The sample of the second stage consisted of 26 women and 23 men aged 18 to 34, M = 23.08 ± 0.65 (SD = 4.52) years. Therefore, only data from those 49 subjects were used for statistical tests for G1 and G2. G3 corresponds to the third try, at home on subjects' own PC. Repartition of subjects within groups for the first stage was as follow: n = 19 for group A, n = 16 for group B and n = 14 for group C.

In-Game Score (IGS): In-Game Scores decreased for the three groups during the third try, one month after, compared to the second try. Yet, the group with cyclical stereoscopy every 1 minute (group B) did not decrease as much as the group with cyclical stereoscopy every 3 minutes (group C).

Response Time (RT): for group A, there was a significant difference in G2's and G3's Response Time. For group B, there was no statistical difference. For group C, there was a significant difference in G2's and G3's Response Time.

4.2.3 Learning results' Summary

There is a significant improvement between the first (G1) and second try (G2) for both In-Game Scores and Response Time for Short Term Learning. Between groups comparison did not show statistical difference (see Tab. 3). There is a significant diminution between the second try (G2) and the third try one month later (G3) for group A and C but not group B for both In-Game Scores and Response Time kept. Between groups comparison did not show statistical difference (see Tab. 4). These results support H3 stating that learning is improving between first and second try with cyclical-S3D in a SG via VR-HMD. But it does not support H4 stating that learning curves are higher with cyclical-S3D than S3D in a SG via VR-HMD.

4.3 Quality of experience (QoE)

4.3.1 Visual discomfort

All 11 items from the questionnaire by Zeri and Livi were combined to test visual discomfort. The higher the score, the more subjects reported visual discomfort.

A non-parametric Friedman test of differences among repeated measures was conducted and rendered a Chi-square value of 11.70 which was significant (**p = .003**). A Pairwise Durbin-Conover post-hoc test was conducted and showed a significant difference in visual comfort for group A (*M* = 1.80, *SD* = 0.93) and group B (*M* = 1.54, *SD* = 0.78), **p = .001**; no significant difference in visual comfort for group A and group C (*M* = 1.89 *SD* = 1.12), p = 0.54; a significant difference in visual comfort for group B and group C, **p = .008**. Overall visual discomfort was reported as low by subjects, with medians ranging from 1 to 2.

Group B reported a lower visual discomfort than group A and group C. Group C reported a lower visual discomfort yet not statistically different from group A (*Fig. 6*).

4.3.2 Presence

All 10 items from the questionnaire by Makransky *et al.* were combined to test presence. The higher the score, the more subjects reported high presence. A non-parametric Friedman test of differences among repeated measures was conducted and rendered a Chi-square value of 4.26 which was not significant (p = 0.12). Despite Friedman test result, a Pairwise Durbin-Conover post-hoc test was conducted and showed **a significant difference in presence for group A (*M* = 3.40, *SD* = 0.91) and group B (*M* = 3.07, *SD* = 1.23), p = .042**; no significant difference in presence for group A and group C (*M* = 3.24 *SD* = 1.06), p = 0.48; no significant difference in presence for group B and group C, p = 0.18.

Overall presence was reported as medium or lightly high by subjects, with medians ranging from 3 (group B) to 4 (group A and C). Group B reported a lower presence than group A indicating a negative impact of cyclical stereoscopy with 1 minute cycles over QoE.

4.3.3 Flow

All 9 items from the questionnaire by Rheinberg, Vollmeyer and Engeser were combined to test flow. The higher the score, the more subjects reported high flow. A non-parametric Friedman test of differences among repeated measures was conducted and rendered a Chi-square value of 18.90 which was significant (**p = < .001**). **A Pairwise Durbin-Conover post-hoc test was conducted and showed a significant difference in flow for group A (*M* = 3.63, *SD* = 0.87) and group B (*M* = 4.00, *SD* = 1.23), p = < .001; a significant difference in presence for group A and group C (*M* = 3.83 *SD* = 0.85), p = .012;** no significant difference in flow for group B and group C, p = .056.

Overall flow was reported as lightly high by subjects, with medians at 4 (for all groups). Group A reported a lower flow than group C and B indicating a positive impact of cyclical stereoscopy with 1 minute cycles and 3 minutes cycles over QoE (*Fig. 7*).

5 Discussion

5.1 Cyclical stereoscopy

Our hypothesis was that optometric variables are different between pre- and post- measurements after exposition to cyclical-S3D in a SG via VR-HMD (H1). Since PPA and Visual acuity are statistically different between pre- and post- exposure, the hypothesis can be supported. Yet, Stereoscopic acuity and Ease of Accommodation did not differ statistically. The overall effect of cyclical-S3D seems negative over visual fatigue as for regular S3D.

Our hypothesis was that S3D leads to a higher visual fatigue than cyclical-S3D in a SG via VR-HMD (H2) as getting back to bi-ocular imaging would relax vergence and alleviate conflict with accommodation. For the following optometric variables, cyclical stereoscopy tended to be more tiring: Punctum Proximum of Accommodation (PPA), Ease of Accommodation (EoA). Only Stereoscopic Acuity (SA) showed a contrary tendency. However, Visual Acuity showed a statistical difference between group B (cyclical stereoscopy every 1 minute) and group A (stereoscopy): cyclical stereoscopy every 1 minute is more tiring than stereoscopy. Cyclical stereoscopy every 3 minutes tends to be more tiring than stereoscopy although no statistical difference have been found. Therefore, contrary to our hypothesis, cyclical-S3D in a SG via VR-HMD leads to a higher visual fatigue than S3D. H2b which stated that a difference would be significant between the two cyclical stereoscopy conditions can not be supported.

These results would favour Cai *et al.* findings that the process of activating stereopsis is more tiring than its sustaining process [16]. Reactivating stereopsis cyclically impacts negatively the visual system as stimuli implies more work for it to adapt to the virtual environment's depth cues.

Our results are not in line with previous one from Matsuura who reported a decrease in visual fatigue [21]. This difference can be explained by several experimental conditions: 1) Matsuura's results are relying only on questionnaires, not optometric variables, 2) our virtual environments are not alike, 3) stereoscopy is not displayed by the same apparatus as we used a HMD, 4) cyclical stereoscopy was displayed only at the beginning of the exposure while ours was displayed cyclically during the whole exposure time, 5) Exposure duration: Matsuura's exposure duration to stereoscopy was about 20 minutes and less than 10 minutes for cyclical stereoscopy but our conditions were tested during 34 minutes. Our results are not in line with Bouaniche and Leroy's results either [22]. Each element pointed out except concerning the use of optometric variables to assess visual fatigue also apply with their study for explaining such differences.

The variable that varied the most in our study is Visual Acuity which was the more negatively impacted by cyclical stereoscopy with 1 minute cycles. The study by Guo *et al.* showed different results as their group with breaks during exposure (for resting subjects) presented less fatigue [24]. The results difference between our study and Guo *et al.* can be explained by exposure time and stimuli type as visual tasks are more difficult in their study. Other studies are pointing out the fact that bi-ocular imaging would be more tiring than stereoscopy because with HMDs, the more natural viewing despite the vergence-accommodation conflict with stereoscopy [1].

Therefore, cyclical stereoscopy displayed cyclically has effects over visual fatigue. Based on our results, these effects seem negative. Cyclical stereoscopy displayed cyclically is not efficient for reducing visual fatigue. Trying to apply intermittence only at the begging or at the end like previous studies could help better compare results with previous works.

5.2 Learning

Our hypothesis was that learning would improve between first and second try with cyclical-S3D in a SG via VR-HMD (H3). This hypothesis can be supported as there are statistical differences between G1 and G2 for both condition B and C.

Our hypothesis was that learning curves are higher with cyclical-S3D than S3D in a SG via VR-HMD (H4). For Short-Term Learning curves, In-Game Scores tend to be higher with the regular stereoscopy condition rather than the one with cyclical stereoscopy, the 1 minute cycles group being the less efficient. However, Response Time has a better evolution with cyclical stereoscopy with 3 minutes cycles than regular stereoscopy and again cyclical stereoscopy with 1 minute cycles being the less efficient. There is no statistical difference among groups. For Long-Term Learning curves, In-Game Scores tend not to decrease as much for the group exposed to cyclical stereoscopy with 1 minute cycles as for the regular stereoscopy group and the cyclical stereoscopy group with 3 minutes cycles. However, Response Time evolution tends to be better for the cyclical stereoscopy with 3 minutes cycles than the regular stereoscopy one and the cyclical stereoscopy with 1 minute cycles has the worst evolution. None of the statistical tests showed a difference between groups in either Short-Term Learning curves or Long-Term Learning curves.

Discussing our results based on previous literature seems too uncertain as the context is very different. Yet, visual fatigue was higher with cyclical stereoscopy with 1 minute cycles and this condition is mostly the one that has a lower learning curve for short and long-term learning (except for G3's in-game scores). Daniel and Kapoula's work showing a link between vergence-accommodation conflict and work load, could offer a lead for our results [5]. The more visual fatigue, the less subjects are learning efficiently. Since group A and group C have visual fatigue that are alike, effects on learning is similar. Yet, response time curves for group C during short term learning is better than group A.

Therefore, in accordance with our hypothesis (H3), short-term learning is improving in cyclical-stereoscopy. But contrary to our other hypothesis (H4), learning curves are not higher with cyclical-S3D than with S3D in a SG via VR-HMD.

5.3 Quality of Experience

Our hypothesis was that quality of experience is higher with cyclical-S3D than S3D in a SG via VR-HMD (H5).

Visual discomfort: The cyclical stereoscopy with 1 minute cycles (group B) group reported a lower visual discomfort than the stereoscopy (group A) group and cyclical stereoscopy with 1 minute cycles (group C) group. The group with regular stereoscopy is the one that reported the highest visual discomfort. There is a statistical difference between the group B and the group A. Such results are surprizing as subjects from group B showed the most degradation over their optometric variables but reports the higher comfort. Although the two methods are not measuring the same thing, they are supposed to behave in correlation [32]. Such a phenomenon has also been documented by Guo *et al.* study which they explain by getting back to the real-world during breaks [24]. Since our subjects were constantly wearing the HMD but rated discomfort after exposure, this phenomenon could also apply in our study.

Presence: The cyclical stereoscopy with 1 minute cycles (group B) group reported a lower presence than the stereoscopy (group A) group, with a statistical difference. The cyclical stereoscopy with 3 minutes cycles group also reported a lower presence than the regular stereoscopy one, without a statistical difference. This result is not in line with the two other Quality of Experience results. Such difference could be explained by the known limits with such questionnaires [35]. Yet, the result is in line with optometric measure and learning curves.

Flow: the regular stereoscopy group (group A) reported a lower flow than the cyclical stereoscopy with 3 minutes cycles group (group C) and the one with 1 minute cycles group (group B) indicating a positive impact of cyclical stereoscopy with 1 minute cycles and 3 minutes cycles over. Relaxing vergence could help subjects better concentrate on content without facing negative effects of stereoscopy displaying (e.g. doubled viewing).

Visual discomfort and flow are in line with our hypothesis that quality of experience is higher with cyclical-S3D than S3D in a SG via VR-HMD. Yet, Presence is not line with measurements of visual fatigue and learning curves.

5.4 General discussion and Limitations

General limits should be considered with our present results: 1) we used optometric measures that are easy to deploy, yet more precise tools, like eye-tracking, could lead to more meaningful and strong results, 2) the evaluation of quality of experience have been done through questionnaires. Assessing subject's behaviour during exposure could give more insights on it, 3) we chose to use a virtual environment with very low disparity, almost no moving objects, subjects were setting on a chair which is preserving from other strong sensorimotor conflicts (e.g. cybersickness due to vection), 4) visual tasks were very easy which can affect results [36] as pointed out by *Zou et al.*, and could affect the general state of subjects [1], 5) the general characteristics of the chosen HMD (Samsung Gear VR) are low compared to other devices on market (e.g. HTC Vive or Oculus Rift) which influenced the data collection. For

instance, peripherical viewing could impact results as the Samsung Gear VR has a 90° FoV. Using more complex visual tasks and HMDs could give more insights on cyclical stereoscopy effectiveness.

Those points should be considered in order to understand sometime contradictory results between quality of experience and metrics of learning and visual fatigue in our study. Yet, the overall results show that cyclical stereoscopy is not efficient to reduce visual fatigue with low disparity and low interaction contents for learning purposes.

6 Conclusion

This study aimed to assess effects of cyclical stereoscopy imaging in a Samsung Gear VR HMD (with a S6) while training for a job interview. Our results show that the impact of such treatment is almost null or negative on visual fatigue based on visual acuity variable when the virtual environment has low depth discrimination tasks and low disparity. This goes in line with Cai *et al.* indicating that the process of activating stereopsis is more tiring than its sustaining process [16]. Previous studies that showed encouraging results with intermittent stereoscopy were activating stereoscopy only at the beginning or at the end of a task [21], [22]. But we choose to activate it several times during exposure (cyclically) as for virtual environments with more complex visual tasks than ours, stereoscopy could be more necessary for task fulfilment and therefore be activated when visuo-spatial tasks are to fulfil. The learning curves show no statistical differences between groups but there is an improvement of short-term learning in groups with cyclical stereoscopy. Yet, cyclical stereoscopy did not lead to a higher learning efficiency than regular stereoscopy. The quality of experience was higher with cyclical stereoscopy based on visual comfort and flow but lower than regular stereoscopy based on presence. Quality of experience seems higher with cyclical-S3D than S3D in a SG via VR-HMD.

Cyclical stereoscopy should be tested with other contents for learning purposes with more visuo-spatial tasks, movements in the virtual environment and other HMDs (higher quality). This would allow the assessment of visual fatigue in different conditions in order to find additional reduction strategies. Material such as eye-tracking should be considered for measuring visual fatigue as new HMDs are implementing it.

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