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The visual impact of augmented reality during an assembly task

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Abstract

Many studies have shown the benefits of augmented reality (AR) to improve manufacturing and control processes in industry. However, the presentation of AR content through optical see-through head-mounted displays may induce unnatural viewing conditions, which consequences on the user's visual system have not been investigated yet. This study aimed at assessing whether using AR instructions to guide a manual task, i.e., conditions where the user is forced to repeatedly look at and accommodate in different planes to extract information from both real and virtual environments, could potentially impact the visual system of operators. A before/after design study was carried out, asking 26 participants to perform Lego assemblies for 30 minutes with either paper or AR instructions. The effects of using AR compared to paper instructions were evaluated both on binocular vision, with classical optometric measurements, and on visual fatigue, with the Virtual Reality Symptoms Questionnaire. No clinically significant differences in optometric measurements (far/near visual acuity, stereoacuity, phoria, convergence, fusional amplitude, accommodation amplitude, accommodative convergence) have been found between AR and paper instructions, and only negligible fatigue symptoms have been seen specifically for AR. Results from both objective and subjective measurements suggest that there is no impact of AR on the oculomotor system and that, in this specific case of use, AR can be safely used for production operators.

Keywords: augmented reality, optometry, visual fatigue, manual assembly, vergence-accommodation conflict, focal distance switching.

1. Introduction

Augmented reality (AR) is the superimposition of digital information (usually a virtual image) on a real scene to enhance the user's experience. Since its beginning in the early 90s, associated technologies have progressed tremendously, and AR is now expected to play an increasing role in various fields, especially in industry. With its strong potential to improve manufacturing and control processes [1], AR has been identified as a key enabling technology for Industry 4.0. For instance, AR can help reducing the duration of manual assembly tasks [2,3], reducing mental workload [4,5] as well as increasing accuracy while performing manual tasks [6,7].

AR content presented through optical see-through head-mounted displays may impose unnatural viewing conditions, and therefore potentially affect the user's visual system (visual discomfort, fatigue,

perturbation of the oculomotor system) and its performance. Although many studies have focused on benefits of AR regarding performances, proportionally few papers have investigated the potential effects on the oculomotor system.

Main visual issues associated with optical see-through AR are the well-known accommodation-vergence (A/V) conflict, the focal rivalry [12], the focal distance switching and the context switching [13]. The A/V issue associated with stereoscopic displays has already been widely reported in the literature with stereoscopic TV, haploscope, and virtual reality (see [8–11] for interesting reviews). Other issues have mostly been studied through the way they affect performance but not the oculomotor system. Condino, Carbone, Piazza, Ferrari & Ferrari [12] studied the impact of focal rivalry and A/V conflict on perceived workload, comfort, and users' visual performance. Gabbard, Mehra & Swan [13] assessed the impact of context switching and focal distance switching on visual performance (task completion and accuracy) and eye fatigue. Therefore, no study yet has assessed visual fatigue with AR, using quantitative evaluation of optometric parameters, such as the ones



Figure 1 - A component assembly station at elm.leblanc factory, in which paper instructions (upper left part of the image) will be replaced by augmented reality instructions.

proposed for other stereoscopic displays.

The present study is part of the IRON-MEN project, which aims at integrating augmented reality technology into production lines in elm.leblanc factories. In this context, the aim of the study was to assess if visual issues associated with AR, could potentially impact the visual system of operators working with AR helmets. Therefore, we considered the case of production operators working on an assembly line. On the chosen assembly workstation (see Fig. 1), operators must perform 3-minute cycles during which they must assemble a set of small parts. Different assembly steps to follow are detailed in a paper booklet containing textual instructions and photos. This paper medium is placed in front of the operator, both above the boxes that contain the pieces to use, and the area where the

operator performs manual assembly. To assess whether working with AR in such conditions could present a risk or lead to discomfort for the user's visual system, we defined a laboratory environment and an assembly task consistent with the workstation in elm.leblanc factory. Thus, participants were asked to perform an assembly task of Lego® blocks. Lego blocks assemblies allow to simulate manual tasks that require manipulation of small pieces, and they have frequently been used in studies about AR and manual assembly [5,14,15]. The Lego models selected for this study took 3 to 4 minutes to assemble. In addition, the participant's assembly station was similar to the one in the factory, with AR instructions displayed in front of the participant, above the location where the Lego blocks are available.

In accordance with similar studies, a pre/post design study was carried out [16,17], in which participants were asked to perform Lego assemblies for 30 minutes [18] with either paper or AR instructions [2]. In order to evaluate the potential impact on the visual system, a procedure like those already widely used for the study of stereoscopic devices [16,19–21] was applied. The effect of using AR was evaluated both on binocular vision with classical optometric measurement, and on visual fatigue with the Virtual Reality Symptoms Questionnaire [22].

2. Methods

2.1 Participants

Twenty-six participants (7 females, 19 males) were recruited for the experiment. Participants included in this study were aged between 24 and 46 years old ($M=28.74$, $SD=5.16$). Participants used optical correction in their usual format (glasses or contact lenses). Exclusion criteria, such as monocular visual acuity lower than 10/10, presence of a fixation disparity, and any ocular pathology, were defined. Considering to those criteria, 3 participants were excluded. Hence, statistical analyses were realised on 23 participants. Prior to participation, all volunteers were fully informed about the experimental procedure, and signed an informed consent form. The study was conducted according to the tenets of the Declaration of Helsinki.

2.2 Material

A HoloLens augmented reality device (Microsoft Corporation, Redmond, WA, USA) was used during the assembly session guided with AR instructions. The HoloLens has a total mass of 579 g, a 30°x17.5° field-of-view, an automatic pupillary distance calibration and a fixed focal distance of 2m. This helmet has previously been used in several studies [12,23]. The Lego® building instructions booklet (20x12cm) was used during the assembly session guided with paper instructions.

12 different models of Lego (e.g., a bike, a camera) were used in the experimental procedure. The Lego models required 11 to 37 assembly steps ($M=20$). Given the number of steps to follow, it was not possible for participants to performed the assemblies without looking to each instructions step. The order in which those models were presented to participants was always the same, and each model could only be assembled once.

2.3 Procedure

Before the study began, participants gave information about their age and all possible antecedents of ocular pathology, surgery, and back or neck issues. Each participant had to perform the experiment in two conditions (i.e., control and RA), during two separate sessions with an interval of 1 to 6 days. Half of the participants did the AR condition the first day, and the other half performed the control condition. During each session, tests measuring optometric parameters and visual fatigue were carried out during 15 min, both before and after assembly task.

Optometric measurements

Some of the optometric measurements were carried out using the Binoculus (Orthoptica®). The Binoculus is a digital platform that allows to display optometric tests (Fig. 2), which present a strong correlation with classic clinical tests [24].

In each test session (i.e., before and after), the following optometric parameters were measured in the order listed below:

1. Monocular visual acuity at distance (3m; Binoculus) and near (0.33m; Parinaud scale) with habitual correction
2. Stereoacuity at distance (3m; Binoculus)
3. Vertical fixation disparity (0.5m) (fixation disparity plank [25])
4. Vertical phoria at distance and near (3m and 0.33 m), with a cover test and Berens prism bar.
5. Amplitude of fusion at distance and near (3m and 0.33 m), for divergence and convergence with Berens prism bar.
6. Monocular accommodation amplitude, with the “Push-Up” method (Parinaud scale)

Accommodative convergence (AC/A ratio) was determined using the phoria method. Calculated AC/A was obtained using the following formula: $AC/A = IPD + (D' - D) / N$

where IPD is the interpupillary distance in centimetres, D' corresponds to near phoria, D to far phoria in dioptres, and N to near-fixation distance in dioptres.

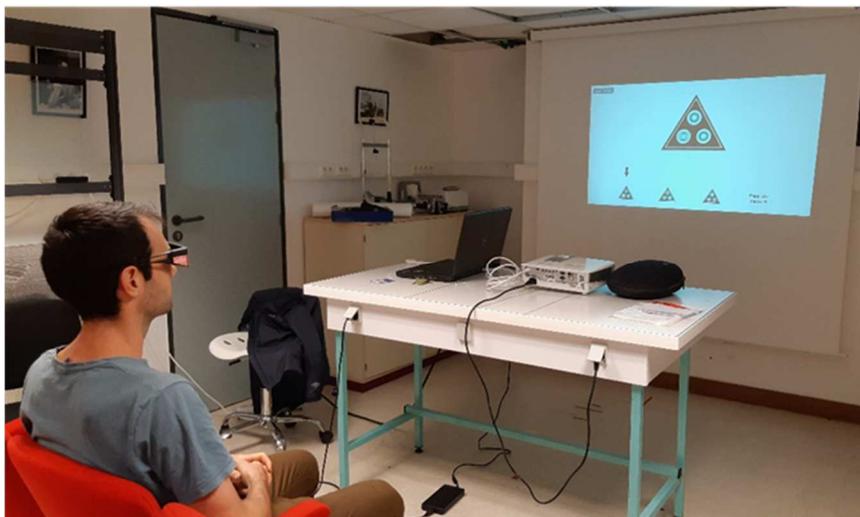


Figure 2 - Participant during stereoacuity test in the experimental room using the Binoculus.

Questionnaire

Once the optometric measurements were achieved, fatigue symptoms were assessed using the Virtual Reality Symptoms Questionnaire [22]. This questionnaire was developed from a list of the most frequently reported symptoms following virtual reality viewing. It is composed of 13 symptom questions, with 8 general and 4 eye-related (due to a semantic proximity in French between *Tired eyes* and *Eyestrain*, only *Eyestrain* item was used), rated on a 7-point scale (with 0 for “none”, 1 and 2 for “slight”, 3 and 4 for “moderate”, 5 and 6 for “severe”).

Assembly task

The assembly task was performed in two different conditions, with AR instructions or with original Lego paper instructions, hereafter respectively designated as “AR” and “Control”. In both conditions, participants had to assemble different models of Lego blocks for 30 minutes. Since the aim of this experiment was to evaluate the impact on vision and not on performance, no time pressure was placed on participants. Participants had to complete the largest number of Lego models that they could in 30 min, at their own pace. Once a model was finished, they performed the next one. Participants performed the assembly task standing at a table 97cm high, in front of a wall 81cm away (see Fig. 3). The table and wall were homogeneously illuminated (100 lux).

In the AR condition (see Fig. 3), a virtual interface allowed one to see the different pictures of the instruction step, and on each side, two different arrows allowed the user to move on the next step or to return to the previous one. In a short phase preceding the assembly task, participants were explained how to optimally position the AR device on their head to ensure comfortable movement, and how to interact with the interface. The use of the HoloLens can be compared to a computer mouse. A white dot follows the user's head movements and acts as a cursor, and a hand gesture allows the user to click and to move between different steps. The AR interface was placed in front of the participant, projected at 3m, with a fixed focal distance at 2 m, and had a real size of 1mx0.70m (i.e., approximately 19°x13°). In this condition, the change of the subject's gaze between instructions and Lego blocks implied a change in accommodation demand. The user focused alternately on the Lego blocks and on virtual information (AR instruction interface). There was a focal distance difference between 0.70m (1.43 D) and 3m (0.33D).

In the control condition, the paper instructions were the ones provided by Lego® in the original box. This booklet was placed on the table, on the left side of the Lego blocks. As instructions were the same as in AR condition, the number of steps and the switching rate were supposed to be the same. However, in control condition, the change of the subject's gaze between instructions and Lego blocks did not imply a change in accommodative demand.

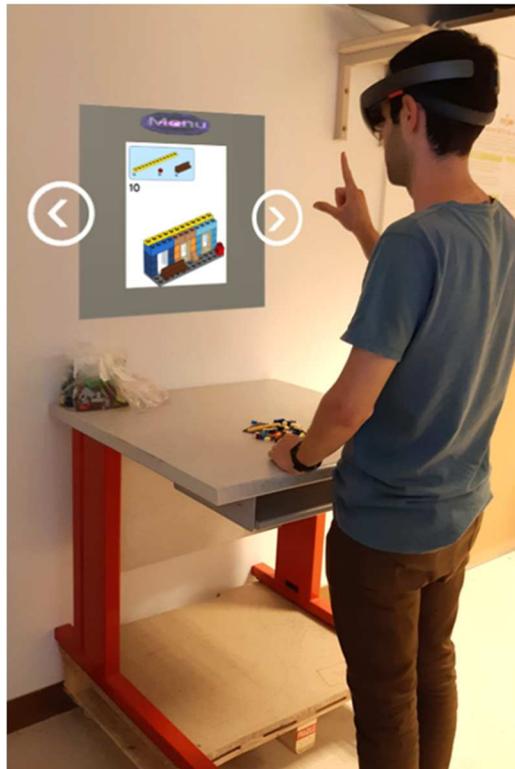


Figure 3 - Participant during assembly task in AR condition. In order to represent what participants see in the helmet, a simulation of the AR interface has been added to the picture.

2.4 Statistical Analyses

Statistical analyses were performed with JASP (JASP Team, 2019). A 2x2 within-subject ANOVA, with instructions conditions (AR, control) and test session (before, after) was calculated for each parameter, to evaluate whether the use of AR leads to changes in binocular vision and fatigue, and if they are different from changes retrieved with control condition. As normality distribution assumption was violated, we ran the non-parametric adjusted rank transformed (ART) ANOVA (Leys & Schumann, 2010). Given that pattern of results observed with ART ANOVA was identical to those observed with parametric ANOVA, we only present the latter below.

3. Results

Original raw data of this study including optometric measurements and subjective scores of VRSQ are available at Mendeley Data (<http://dx.doi.org/10.17632/rpsvy6b23g.1>) [26].

3.1 Optometric measurements

Table 1 presents the means and standard deviations of optometric tests, for instruction conditions (i.e., AR condition and control condition), before and after assembly task. Analyses revealed an interaction effect between instruction conditions and test session on stereoacuity (Fig. 4), $F_{1, 21}=12.03$, $p=0.028$, $\eta_p^2=0.36$. Simple effect analyses showed that there was a significant difference in stereoacuity between test session, for AR condition, $F_{1, 21}=9.54$, $p=0.006$, but not for control condition

$F_{1,21}=3.30$, $p=0.08$. In AR condition, the stereoacuity was better after assembly task than before, whereas no significant difference was observed after assembly task in control condition.

Table 1 - Means and standard deviations of optometric tests, for instruction conditions, before and after the assembly task.

Optometric parameters	Test session	
	Before M (SD)	After M (SD)
Far visual acuity (x/10th)		
AR	9.96 (0.21)	10.00 (0.00)
Control	9.98 (0.10)	10.00 (0.00)
Near visual acuity (x/10th)		
AR	10.00 (0.00)	10.00 (0.00)
Control	10.00 (0.00)	10.00 (0.00)
Stereoacuity (arc sec)		
AR	55.00 (20.18)	47.27 (15.79) **
Control	50.00 (16.04)	54.55 (21.54)
Far vertical phoria (D)		
AR	0.00 (0.85)	-0.10 (0.73)
Control	-0.17 (0.83)	-0.17 (0.83)
Near vertical phoria (D)		
AR	-0.17 (1.59)	-0.10 (1.28)
Control	-0.35 (1.30)	-0.35 (1.77)
Fusional amplitude		
Far divergence (D)		
AR	6.00 (2.00)	6.35 (2.23)
Control	6.35 (2.31)	6.61 (2.86)
Far convergence (D)		
AR	16.52 (6.68)	18.83 (9.24)
Control	16.56 (7.51)	17.96 (6.72)
Near divergence (D)		
AR	10.61 (5.06)	11.74 (4.53)
Control	10.26 (4.53)	10.70 (4.54)
Near convergence (D)		
AR	25.52 (8.88)	25.04 (9.43)
Control	22.17 (8.26)	23.13 (8.76)
Accommodation amplitude (cm)		
AR	15.50 (3.66)	15.79 (6.54)
Control	15.41 (3.83)	15.51 (3.60)
Accommodative convergence (MA/D)		
AR	6.20 (0.52)	6.26 (0.47)
Control	6.20 (0.45)	6.20 (0.53)

Asterisks refer to a significant difference in the variables before and after the assembly task. * Significant at 0.05; ** significant at 0.01.

A main effect of test session was found on fusional amplitude for convergence at far distance. Fusional amplitude was higher after the assembly task than before, $F_{1, 22}=6.40$, $p=0.019$, $\eta_p^2=0.23$. For convergence at near distance, analyses showed a main effect instruction conditions, fusional amplitude was lower for control than for AR, $F_{1, 22}=6.36$, $p=0.019$, $\eta_p^2=0.23$.

For all other optometric measurements, all other main effects and interactions were non-significant (with all $ps > 0.062$).

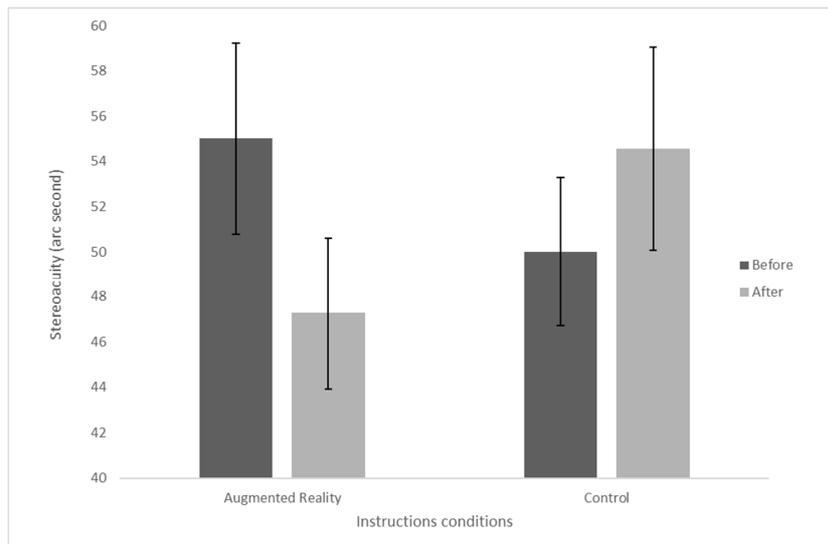


Figure 4 - Stereoacuity scores in arc second, in augmented reality and control conditions, before and after assembly task. Error bars represent standard error.

3.2 Fatigue symptoms

Table 2 presents the mean and standard deviation of symptom scores, for instruction conditions, before and after assembly task. Regarding symptoms of blurred vision (Fig. 5a), a main effect of instructions was found, with participants reporting higher score of blurred vision for AR than for control, $F_{1, 22}=7.01$; $p=0.015$, $\eta_p^2=0.24$. A main effect of test session was also observed, indicating that blurred vision scores were lower before assembly task, than after, $F_{1, 22}=4.43$, $p=0.047$, $\eta_p^2=0.17$. A significant interaction between instructions and test session was also found, $F_{1, 22}=4.31$, $p=0.050$, $\eta_p^2=0.16$. Simple effect showed that blurred vision scores reported by participants were significantly different between test session, in AR condition, $F_{1,22}=5.46$, $p=0.029$, but not in control condition $F_{1,22}=0.32$, $p=0.58$. After assembly task in AR condition, participants notified higher blurred vision scores than before, whereas after assembly task in control condition, the scores were like before.

For sore/aching eye symptoms (Fig. 5b), analyses showed the effect of test session, symptoms after assembly task were higher than before, $F_{1, 22}=8.63$, $p=0.008$, $\eta_p^2=0.28$. A significant interaction between instructions and test session was found, $F_{1, 22}=7.01$, $p=0.015$, $\eta_p^2=0.24$. Simple effect analyses showed that sore /aching eye scores were significantly different between test session, in AR, $F_{1,22}=13.92$, $p=0.001$, but not in control $F_{1,22}=0.35$, $p=0.26$. In AR condition, sore /aching eye symptoms were higher after assembly task than before, whereas in control condition, the score after assembly task was like before.

Table 2 - Mean and standard deviation of the score of the virtual reality symptoms questionnaire, for instruction conditions, before and after assembly task.

Symptoms	Test session	
	Before M (SD)	After M (SD)
General discomfort		
AR	0,44 (0,79)	1.83 (1.44)
Control	0.57 (0.95)	1.35 (2.27)
Fatigue		
AR	1,22 (1,24)	1,87 (1,25)
Control	0,91 (0,95)	0,96 (1,14)
Boredom		
AR	0.13 (0.34)	0.78 (1.09)
Control	0.13 (0.34)	0.35 (0.57)
Drowsiness		
AR	0.52 (0.67)	0.70 (0.88)
Control	0.44 (0.84)	0.35 (0.65)
Headache		
AR	0.30 (0.64)	0.96 (1.15) **
Control	0.39 (0.89)	0.48 (0.85)
Dizziness		
AR	0.04 (0.21)	0.30 (0.77)
Control	0.09 (0.29)	0.09 (0.29)
Difficulty concentrating		
AR	0.22 (0.42)	0.44 (0.66)
Control	0.22 (0.52)	0.39 (0.66)
Nausea		
AR	0.00 (0.00)	0.09 (0.42)
Control	0.00 (0.00)	0.00 (0.00)
Sore/aching eyes		
AR	0.35 (0.49)	0.96 (1.02) ***
Control	0.52 (0.85)	0.70 (0.93)
Eyestrain		
AR	0.74 (0.92)	1.74 (1.36)
Control	0.87 (1.10)	1.13 (1.18)
Blurred vision		
AR	0.17 (0.39)	0.52 (0.79) *
Control	0.13 (0.34)	0.17 (0.39)
Difficulty focusing		
AR	0.22 (0.42)	0.48 (0.79)
Control	0.17 (0.39)	0.13 (0.34)

Asterisks refer to a significant difference in the variables before and after assembly task. * Significant at 0.05; ** significant at 0.01; *** significant at 0.001.

Regarding headache symptoms (Fig. 5c), analyses revealed a significant main effect of test session, with higher symptoms after than before, $F_{1, 22}=9.72$, $p=0.005$, $\eta_p^2=0.31$. An interaction was observed between instructions and test session, $F_{1, 22}=5.45$, $p=0.029$, $\eta_p^2=0.20$. Simple effect analyses showed that there was a significant difference in headache score between test session, for AR condition, $F_{1,22}=11.20$, $p=0.003$, but not for control condition $F_{1,22}=0.39$, $p=0.54$. In AR condition,

headache after assembly task was higher than before, whereas in control condition, headache after assembly task was like before.

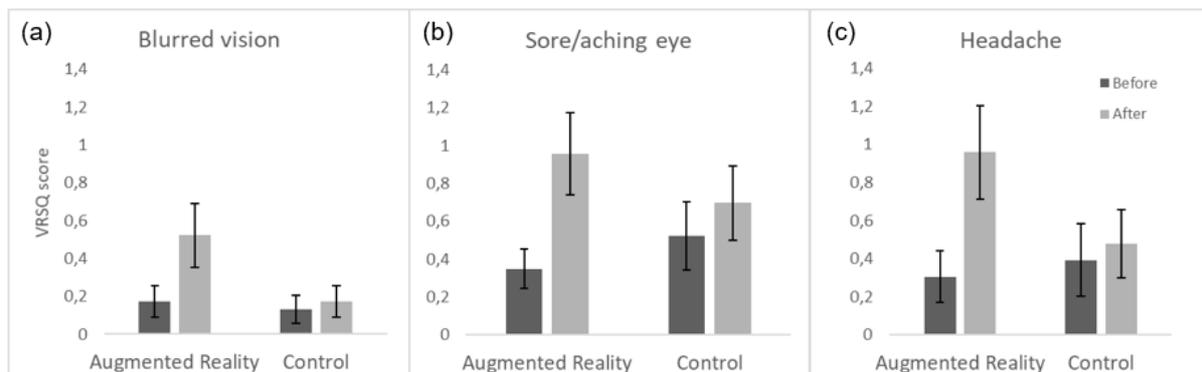


Figure 5 - Scores of blurred vision (a), sore/aching eyes (b), and headache (c) for augmented and control condition, before and after assembly task. Error bars represent standard error.

For fatigue symptoms, a main effect of instructions was found, fatigue was higher in AR than in control, $F_{1, 22}=7.66$, $p=0.011$, $\eta_p^2=0.26$. An effect of test session was found, indicating that fatigue after assembly task was higher than before, $F_{1, 22}=7.66$, $p=0.011$, $\eta_p^2=0.26$.

For the five other symptoms, a main effect of session has been observed. General discomfort after assembly session was higher than before, $F_{1, 22}=16.46$, $p<0.001$, $\eta_p^2=0.42$. Boredom after assembly was higher than before, $F_{1, 22}=12.50$, $p=0.002$, $\eta_p^2=0.36$. Dizziness after assembly was higher than before, $F_{1, 22}=5.31$, $p=0.030$, $\eta_p^2=0.20$. Difficulty concentrating after assembly was higher than before, $F_{1, 22}=5.75$, $p=0.029$, $\eta_p^2=0.21$. Eyestrain after assembly was higher than before, $F_{1, 22}=23.36$, $p<0.001$, $\eta_p^2=0.51$. Nevertheless, for all of these symptoms, the effect of instructions and the interaction were not significant (all $ps>0.057$).

Finally, no significant effects have been observed for drowsiness, nausea, and difficulty focusing symptoms (all $ps>0.057$).

4. Discussion

The goal of the present study was to assess if the considered case of use of AR to guide an assembly task, such as in an industrial context, could negatively affect the production operators' visual system. A before/after study design comparing the effect of AR instructions and paper instructions on 9 optometric measurements as well as VRQS scores was implemented.

For most optometric parameters, no statistically significant differences were found after the use of AR. Only stereoacuity significantly changed specifically after the use of AR and not after the use of paper. Some studies have shown that stereoacuity could be improved with a game in a virtual reality environment. However, those studies usually involved stimuli specifically designed for visual training [27,28]. Furthermore, the difference in stereoacuity in the present study is too small to be considered as clinically significant. Indeed, the difference is smaller than the disparity used as a threshold for the different levels in the clinical test. The use of another stereoacuity test with a smaller threshold could be of interest to assess whether there is adaptation.

Results have shown effects on fusional amplitude for convergence. The main effect of test session observed for far convergence could be explained by a training effect, the fusional amplitude is improved in after test session only because it has been already assessed in the before test session. For near convergence, the measurements are different between both before test sessions, which could explain the significant instruction effect.

Regarding optometric parameters, no statistically significant changes were found, neither for the AR instructions, nor for the paper instructions. Thus, no significant degradation of the oculomotor system specific to AR contents visualization has been observed after 30 min of use. These results are valid for the device used in this case (i.e., the HoloLens). It could explain that our results are consistent with those found for a virtual reality device used by Peli [16], but not with some results obtained with different stereoscopic displays [21,29–31].

The evaluation of subjective fatigue symptoms revealed significant differences between the two instruction conditions. Performing manual tasks with AR instructions led to an increase in some symptoms that were not found with paper instructions. After the use of AR, specifically, participants reported more blurred vision, sore/aching eyes, and headache. However, notice that the subjective ratings are low, and stay confined to the “slight” category. The increase of this subjective rating is coherent with previous findings reported for diverse stereoscopic displays [21,32,33]. This result may be explained by the difference of accommodation demand between the two instruction conditions. Indeed, the position of AR instructions induce changes in accommodation between instructions and Lego, which is not the case with paper instructions. In addition, the increase of these subjective symptoms is not confirmed with optometric measurements. For example, the use of AR is associated with higher symptoms of blurred vision, but without any decrease of accommodation amplitude or visual acuity. This discrepancy between subjective and objective measurements has already been observed in other studies, which suggested a difference between physiological fatigue and subjective discomfort [9,34]. Thus, the combination of the two types of measurements seems necessary to have a complete evaluation of the impact of AR during the period of use.

It was found for an important number of subjective symptoms that there was only a session effect but no instruction effect. This indicates that the assembly task itself was responsible for an increase in general discomfort, boredom, dizziness, difficulty concentrating and eyestrain. Those symptoms seem to be inherent to the realization of manual tasks regardless of the instruction method used to perform it.

Given that the VRQS shares 8 items with the Simulator Sickness Questionnaire [35], it allows us to assess whether the use of AR during 30 min led to symptoms of simulator sickness. AR is not supposed to produce sickness simulation because real environment is always perceived, therefore there is no inconsistency with visual motion cues. As expected, scores obtained before and after use of AR did not reveal any increase of nausea, difficulty of focusing, general discomfort and dizziness. Moreover these results confirm a study in which AR caused only negligible symptoms of simulator sickness [23].

5. Conclusion

To the best of our knowledge, this research is the first known study to examine the effect of AR on the visual system with optometric measurements. Results from objective and subjective measurements suggest that there is no impact on the oculomotor system, with no change in optometric measurements and few fatigue symptoms. Thus, an AR interface like the one developed in our study with the Microsoft HoloLens, can be used to guide manual assembly tasks during 30 min without being more difficult for the oculomotor system than conventional instructions. In the industrial context of elm.leblanc, it could be concluded that this specific case of use with AR is safe for the visual system of production operators.

Although the present study used an experimental environment which tends to reproduce real conditions of use of AR, this environment is nonetheless not strictly equivalent to real industrial working conditions. Thus, this work only constitutes a first step to evaluate the effects of AR on industrial operators and further studies are needed to evaluate changes in the oculomotor system in a realistic environment, e.g., longer period of assembly, more complex tasks, and industrial illumination conditions. Moreover, given the complexity of some industrial assembly tasks, other studies are needed to study other cases of use, such as the superimposition of virtual and real information, which causes focal rivalry.

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