Simulator Sickness in Augmented Reality Training Using the Microsoft HoloLens

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ABSTRACT
Augmented Reality is on the rise with consumer-grade smart glasses becoming available in recent years. Those interested in deploying these head-mounted displays need to understand better the effect technology has on the end user. One key aspect potentially hindering the use is motion sickness, a known problem inherited from virtual reality, which so far remains under-explored. In this paper we address this problem by conducting an experiment with 142 subjects in three different industries: aviation, medical, and space. We evaluate whether the Microsoft HoloLens, an augmented reality head-mounted display, causes simulator sickness and how different symptom groups contribute to it (nausea, oculomotor and disorientation). Our findings suggest that the Microsoft HoloLens causes across all participants only negligible symptoms of simulator sickness. Most consumers who use it will face no symptoms while only few experience minimal discomfort in the training environments we tested it in.

Author Keywords
Augmented Reality; Simulator Sickness; Motion Sickness; Microsoft HoloLens.

ACM Classification Keywords
H.5.1. Multimedia Information Systems: Artificial, augmented and virtual realities.

INTRODUCTION
Concerns about motion sickness motivated a rich body of work in the area of virtual (VR) and augmented reality (AR) over the past years. Starting with the late 90's simulator systems, users can be immersed in an experience characterized by non-standard visual resolution, inadequate sound spatialisation, encumbering interactive devices, and misregistered tracking information [37]. Since then a lot of technological shortcomings were considered when determining how best to design and use interactive training technology. Modern devices have advanced since then and now typically have a wider field of view and possess higher resolution. Nonetheless, motion sickness can still be frequently observed when viewing moving images irrespective of the degree of realism.

Augmented reality has a long tradition in human-computer interaction. The potential advantages of such systems seem almost limitless and appeal to both academic research and industry [4]. There is, however, a need to investigate human factors and cognitive issues with AR that have not received enough attention, since most of the papers are exploring technological and application issues only.

Augmented reality and virtual reality have a lot in common, so it is not far-fetched to assume both could cause the same symptoms. This has not been thoroughly tested so far. The phenomenon of simulator sickness is broad and includes a number of diverse characteristics, which may well differ from virtual reality.

Research into the causes of motion sickness in virtual reality has been ongoing for decades. Studies have evaluated different military simulators [16], factors contributing to motion sickness in virtual environments (VE) [2,23], and explored different theories explaining causes of motions sickness [29,28]. Recent advances in virtual reality have made systems more interactive. Accordingly, cybersickness was studied using the Sony Glasstron [31], the Oculus Rift [8, 26, 36], and the HTC Vive [34]. Though AR studies flag problems with available devices, simulator sickness has not been studied [10] (see section "Related work").

Contemporary virtual reality systems try to reduce motion sickness and ensure safety of the user. To date, however, there have been only a few suggestions how to make systems safer for AR users [33]. The development of augmented reality head-mounted displays appears to have been guided by the assumption that more-realistic simulation (see-through wide field-of-view visual displays can show a detailed representation of real-world environment) can enhance user adaptation to the system and reduce motion sickness. Using the real world as an interaction environment provides for user orientation cues, which should theoretically suppress some or all of the symptoms [16].

In this paper, we investigate this further. We conducted an experiment with end-user participants in three industries (aviation, medical, space) working with two different software applications — a *recorder* — an authoring tool that captures experts' performance, and transfers it to the second app — a *player*, an end-user tool for experience re-enactment. We evaluate the degree and contributing symptoms of simulator sickness found when using Microsoft Ho-

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loLens in augmented reality knowledge-intensive environment.

The contribution of this paper can be summarized as follows. **First,** we report on findings in measuring the degree of simulator sickness of Augmented Reality based procedural training run on the Microsoft HoloLens. Generally, we found an insignificant degree of simulator sickness, while certain factors contributing to the minimal symptoms experienced by some participants will be identified.

Second, we investigate the effects that the 'amount' of augmentation has on users' simulator sickness. Potentially, if the interaction is closely coupled with a physical world (player application handles objects in the real world), it may differ from interaction that focuses more on the augmented world (recorder application works more with the user interface). We therefore compare findings across the two cohorts subjected to the 'authoring' (recorder) and 'using' (player) condition and find that there are slightly higher levels of motion sickness, where there is more virtuality involved. **Third**, we analyse our findings to gain insight and derive recommendations on how to further improve software and hardware. We recommend to increase the field of view, while at the same time introducing smarter resizing of virtual content displayed.

The rest of this paper is organized as follows. First, we summarise related work on simulator sickness with other devices and technologies. Then we describe the user task scenario and software applications tested. Next, we report on the methodology used for the experiment to subsequently introduce our findings. We discuss implications for further development of hardware and software to conclude the paper with a summary and outlook.

RELATED WORK: SIMULATOR SICKNESS WITH OTHER DEVICES AND TECHNOLOGIES, PREVIOUS STUDIES

Definition

Motion sickness refers to adverse symptoms and observable signs that are associated with exposure to real and/or apparent motion [14]. The most prominent explanation for motion sickness is known as sensory conflict theory [24]. It is widely accepted that the primary effect of motion sickness is caused by mismatches between the sensorial stimulation provided by a simulator and the stimulation expected from real-world experiences recorded in the neural pathways [28, 30]. Another way to interpret motion sickness is by referring to the postural instability theory, developed by Riccio and Stoffregen [32]. They claim that one of the primary behaviour goals is to maintain stability, and once this balance is lost, person start to get motion sick.

Simulator sickness is a form of motion sickness that tends to originate from elements of visual display and visuo-vestibular interaction. Some of the signs and symptoms overlap with motion sickness, such as dizziness, fatigue, drowsiness, nausea, headache and general discomfort [18]. Nevertheless, there are some differences. While major motion sickness symptoms are associated with gastrointestinal distress (stomach awareness, nausea), for simulator sickness the root cause is more visual (eyestrain, difficulty focusing, nausea, headache) [18, 19]. Simulator sickness symptoms include nausea, dizziness, spinning sensations, confusion and drowsiness [16].

Cybersickness, on the other hand, is visually induced motion sickness emerging from the immersion in a computer-generated virtual world, resulting from shortcomings of the simulation, but not from the actual situation that is being simulated. The term cybersickness was proposed by McCauley and Sharkey [27] to describe the motion-sickness-like symptoms associated with virtual environments characterised by "far applications involving distant objects, that is, terrain, self-motion (travel) through the environment, and the illusion of self-motion". As there is a clear relation between motion sickness, simulator sickness, and cybersickness (and their symptoms), the underlying physiological causes may be related too [18].

Methods

There are many possible ways to measure simulator sickness [11]. Direct observation of participants is possible during the simulation session, measuring physiological conditions such as heart rate variability, electrogastrogram, respiration rate and stomach activity [3, 6, 40]. Direct observation is popular in medical environments. Past research has provided evidence of the usefulness of self-report methods of motion and simulator sickness measurements. The Pensacola Diagnostic Rating Scale for motion sickness susceptibility is one of them and was proposed in late 70-s., where each symptom level is assigned incremental point values [12]. It is the most widely used tool for motion sickness research and it is used in its original and revised forms. Kennedy, Lane, et al. [18] analyse the factors contributing to simulator sickness and develop and validate an alternative 16-item measurement method, the Simulator Sickness Questionnaire (SSQ). This method allows the identification of symptoms related to disorientation, oculomotor effects, and nausea, as well as the calculation of a total severity score. Furthermore, the Fast Motion Sickness Scale was proposed in [20] as a verbal rating scale to obtain motion sickness data during stimulus presentation. It is a quick method for motion sickness assessment, but the results typically do not differ from SSQ. Though intensively studied, there is a good chance that existing methods for measuring motion sickness do not fully reflect the complexity and range of factors that can contribute to simulator sickness on augmented reality head-mounted devices.

Application

Motion sickness research in virtual environments has been going on for decades, expanding from military (for comprehensive review see [16]) to the medical, educational, and entertainment sectors. Previous studies show that approximately three-quarters of those exposed to simulator system tend to experience some level of nausea, disorientation, and oculomotor problems [6, 7, 9, 25, 35]. Since devices matured over time, we restrict our summary of existing studies to recent ones on modern devices. While users of early VR systems suffer in particular of nausea, provoking stomach awareness and burping [16], modern head-mounted VR displays predominantly affect the oculomotor and disorientation dimensions. The top four scores are general discomfort, eyestrain, difficulty concentrating, and fatigue [15].

Current VR goggles show great variety in designs and tech characteristics. Serge and Fragomeni [34] evaluate the relation of head movement tasks to simulator sickness on the HTC Vive, finding no significant difference between head movement types, but a clear effect of increasing simulator sickness with increasing duration of exposure (mean of 18.23 for total severity after the final session using SSQ method). In an experiment designed to measure simulator sickness in virtual reality using an Oculus Rift and a HTC Vive, disorientation scores were always the highest [35]. Other study remarks mild and moderate nausea as main symptoms with the Oculus Rift, using a different subjective rating scale [8]. Two experiments focused on testing VR driving simulators with the SSQ and discovered oculomotor-related disturbances. Moreover, they found that users with more task-related experience have a lower total severity score [13, 22].

AR optical see-through displays provide interaction with both real and virtual worlds. This allows complementing the physical world with layers of information for hands-free interaction with the environment. There are only a few studies about motion or simulator sickness in Augmented Reality head-mounted displays. Terhoeven et al. [39] investigate how the Epson Moverio BT-300 influences visual comfort when using it in a moving environment. Visuo-spatial abilities were in focus in [41]. Buker et al. [5] study the effect of latency on a Rockwell Collins helmet-mounted see-through display and determine that simulator sickness can be reduced using predictive tracking compensation and when minimising head movements.

Related to this and potentially contributing to motion sickness, Kishishita and colleagues explore how a wider field of view reduces mental workload [21], while [17] focus on psychological and physiological aspects of AR. To summarise, the most common symptoms for simulator sickness in prior studies have to be reported as oculomotor-related disturbances followed by disorientation. Depending on content, conditions, and the actual simulation scenario, the severity of simulator sickness may vary.

THE AR TRAINING HARDWARE AND SOFTWARE SYSTEM

The objective of the subsequently reported experiment was to evaluate an augmented reality training application prototype on a real procedure within three test beds: maintenance training in aviation, ultrasound examination for radiologists, and astronaut training for the space industry. We tested two connected, but independent applications on Microsoft HoloLens glasses, a recorder — supporting experience capturing and functioning as a content creation system, and a player — for experience re-enactment.

The first one is a ***recorder*** — an application for *experts* that helps capture workplace performance (i.e., knowledge and skills). It allows this by providing activity guidance, for example, of how to perform an aircraft assembly procedure by directing attention to relevant parts, overlaying visual annotation to explain step-by-step what needs to be done. Experts work with a graphical menu (*Figure 1*) that presents a set of affordances for creating training content. There are different types of affordances, such as audio, photo, text annotation, 3D model (different pointers, highlighters etc.), recording of a hand movement, which could be attached to a certain point of interest in a physical environment (for instance a button on an ultrasound machine keyboard). As user attention focuses mainly on virtual content generation and the user interface, physical interaction with the real world in this application is rather limited.

Figure 1. Main radial menu of a *recorder* application, which allows to add various types of annotations to a particular point in physical environment.

The second application is a ***player*** — a tool for *learners* for experience re-enactment that receives the recorded training data from the recorder app. It immerses the learners in a training scenario, where they need to follow a sequence of recorded steps to perform a certain procedure, e.g. ultrasound diagnostics (*Figure 2*). In this application, user attention is focused predominantly on the real world, where holding physical objects such as a probe, a screwdriver, or a stowage rack is essential for the success of the training.

METHODOLOGY

Participants

	Aviation	*Medical*	*Space*	*Total*
Expert	21	9	17	47
Learner	34	39	22	95
Excluded	2	2	6	10
Total healthy	53	46	33	132

Table 1. Participants of the experiment by industry

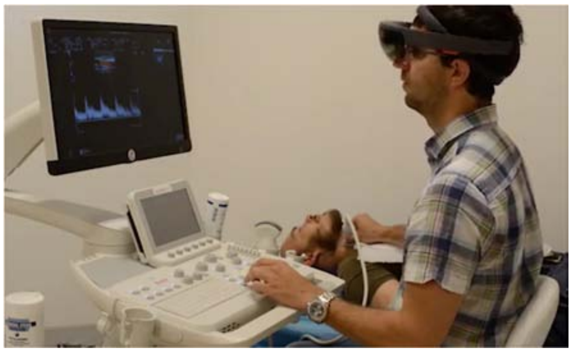

Figure 2. Learner is 'wearing' an expert's experience, performing an ultrasound diagnosis with the *player* application

We tested simulator sickness on a total of 142 subjects (111 males, 31 females) with no prior augmented reality experience (it was an intention to exclude those, experiencing AR before). Age distribution across all test beds: 69 participants were between 18-24 years old, 48 were 25-32 years old, 11 were 35-44 years old, 9 were 45-54 years old, 5 were 55-64 years old, and none of the participants fell into over 65 years category. As advised by [18] and [23] the study was performed only on healthy subjects, excluding the data of subjects who had flagged moderate or severe symptoms in the pre-trial SSQ questionnaire. 10 participants were excluded from analysis in that way due to showing symptoms before exposure and the evaluation was conducted with 132 healthy subjects (*Table 1).*

Experiment design

Simulation equipment

This experiment used the commercially available Microsoft HoloLens head-mounted display. The Microsoft HoloLens was connected to a computer via Wi-Fi (for Mixed Reality Capture) and was used without a clicker hardware.

Procedure

To assess simulator sickness among participants, the simulator sickness questionnaire was used [18]. The SSQ is a self-report checklist with 16 items - symptoms that are rated by participants on a Likert-type scale from 0-3 (none-severe). The SSQ is comprised of three subscales: nausea (N), containing symptoms that are related to gastrointestinal distress such as nausea, stomach awareness, salivation, and burping. The oculomotor (O) subscale relates to eyestrain, difficulty in focusing, blurred vision, and headache. The disorientation (D) subscale is related to vestibular disturbances such as dizziness and vertigo.

Before the trial, demographic information and pre-SSQ were elicited. Participants were excluded from the experiment, if classified as showing symptoms prior to exposure of the HoloLens in the trial (i.e., showing moderate or severe symptoms for any of the 16 SSQ symptoms). Each participant was allocated approximately 40 minutes for the entire session. The session included introductory instructions, collection of personal data, pre-trial SSQ, gesture training (which aims at familiarising the user with the gesture interaction facilities), the actual task (different for each test bed) and post-SSQ.

Test beds

We selected three independent, but related application domains and according testing tasks to be knowledge intensive and procedural by nature. The industries selected — aviation, healthcare, and space — are mature fields with many tools for innovation and thus open to experimentation, while offering clear pathways for exploitation. We focus on improving human performance in the workplace and this selection provided us with a range of testing scenarios and participants. The tasks selected for the tests provide variation in distance to operating environment and overlays, varying posture and location of the participants sitting, standing, moving.

The *aviation trial* was conducted at Lufttransport with the air ambulance plane Beechcraft B200. Experts and learners carried out a pre-flight inspection task, following instruction steps such as checking the baggage compartment, setting elevator trims and landing gear control handles, inspecting ignition switchers, etc. The *medical trial* was conducted at EBIT and devoted to an ultrasound diagnostic training using MyLabEight, an ultrasound machine produced by ESAOTE. The subjects were asked to perform a carotid artery examination and take measurements using a linear probe and the keyboard. The *space trial* took place at ALTEC, where subjects performed an installation of a Temporary Stowage Rack (TSR) in the Automated Transfer Vehicle (ATV) module. The installation of the TSR is a real procedure that astronauts have to perform routinely on the International Space Station in the ATV module.

FINDINGS

In this section we present the main contribution of the paper. First, the simulator sickness scores were calculated for the individual test beds within the three industries.

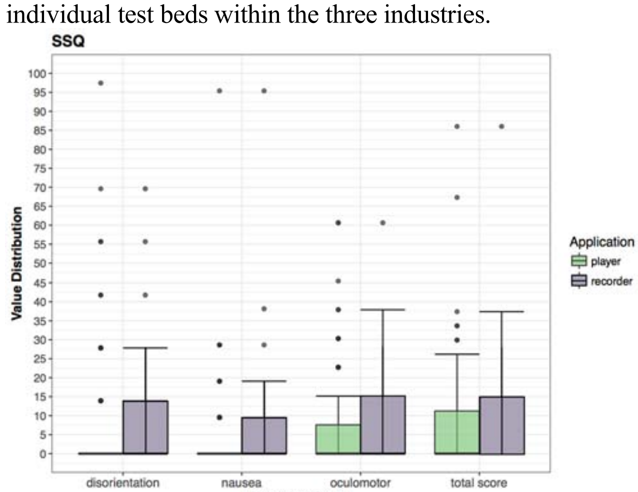

Figure 3. Symptom scores comparing player and recorder

All 16 symptoms were used for calculating Nausea (N), Oculomotor (O) and Disorientation (D), and unit weights were assigned in each category.

	Nausea (N)		Oculomotor (O)		Disorientation (D)		Total Score	
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Aviation	5.58	15.24	7.43	13.74	4.70	13.63	7.12	15.23
Medical	2.75	6.30	7.58	10.80	5.80	14.07	6.39	9.62
Space	4.33	8.29	9.80	12.92	13.07	19.97	10.08	13.33
Player	3.70	11.04	7.51	12.42	6.96	15.97	7.03	12.96
Recorder	6.80	16.56	9.69	14.63	7.44	15.59	9.48	16.36
All	5.14	11.87	9.46	14.44	8.25	17.10	8.65	14.19

Table 2. Mean and standard deviation of simulator sickness for different test beds and applications

For assessing the scores, a 4-point scale was used and weighted values were added to obtain the scores for each category. N, O, D, and Total Score (TS) are then counted using the method described in [19]. *Figure 3* indicates that the symptoms vary across the two conditions participants were exposed to, namely the 'recorder' and 'player' applications. To investigate whether the distribution of the total scores for the participants experiencing the player 'condition' are actually significantly different from the ones experiencing the recorder condition, we first tested whether the Total Score of the player and recorder is normally distributed using the Shapiro-Wilk test.

The test gives a *p*-value below 0.001, i.e., the sample tested is very unlikely to be from a normally distributed population. This requires us to use a one-sample Wilcoxon test, comparing the means for recorder and player. The results suggest that the H_0 hypothesis (of no difference between the means) is rejected with a p-value below 0.001 and hence we conclude that the *recorder experience has a higher* Total Score with a mean of 9.48 compared to the player's mean of 7.03 (*Table 2*). Looking into the symptom groups, *Figure 4* shows further that across three test beds, participants largely did not experience disorientation or nausea, though there were outliers in the data, indicated by the dots in the plot.

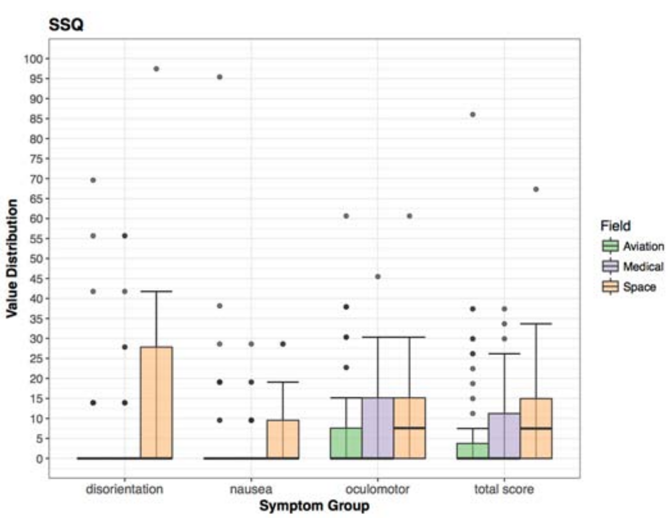

Figure 4. Symptom groups and total scores for each test bed

As we can see in *Figure 4*, oculomotor disturbances are those contributing to simulator sickness the most, followed by disorientation. Individual symptoms, however, may be more informative than the SSQ's Total Score. The simulator sickness symptoms reported by the subjects were not distributed uniformly. There were more oculomotor-related disturbances reported and fewer nausea and disorientation symptoms. The symptom reported the most is *eyestrain*, which was reported in 27 cases as slight and in 5 cases as moderate. Nobody reported any severe symptoms at all.

SSQ	*Mean*	*SD*	*>0*	*N*	*O*	*D*
General discomfort	0.15	0.41	12%	×	×	
Fatigue	0.14	0.37	13%		×	
Headache	0.17	0.43	14%		×	
Eyestrain	0.28	0.53	24%		×	
Difficulty focusing	0.16	0.41	14%		×	×
Salivation	0.05	0.21	5%	×		
Sweating	0.06	0.24	6%	×		
Nausea	0.05	0.26	5%	×		×
Difficulty concentrating	0.08	0.27	8%	×	×	
Fullness of the head	0.09	0.32	8%			×
Blurred vision	0.10	0.30	10%		×	×
Dizziness (eyes open)	0.05	0.21	5%			×
Dizziness (eyes closed)	0.04	0.19	4%			×
Vertigo	0.03	0.17	3%			×
Stomach awareness	0.05	0.24	4%	×		
Burping	0.02	0.15	2%	×		

Table 3. Means, standard deviations, percentage of participants with symptoms for all SSQ indicators (N – nausea, O – oculomotor, D – disorientation)

Table 3 shows allocation of the individual symptoms within symptom groups, where we can see that eyestrain is the main factor contributing to simulator sickness. *Figures 5, 6, 7* show the distribution of the simulator sickness scores comparing player and recorder applications across all the test beds. As we can see from the *Figure 7*, participants exposed to both the player and the recorder apps in the space trial showed higher SSQ scores than those in the space and medical trials.

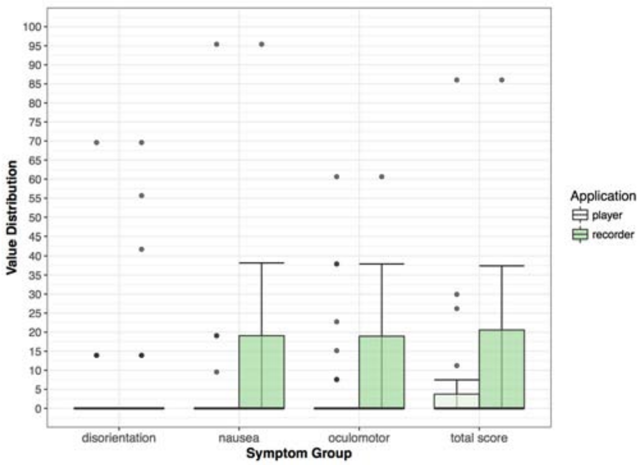

Figure 5. Simulator sickness scores for the aviation trial comparing player and recorder

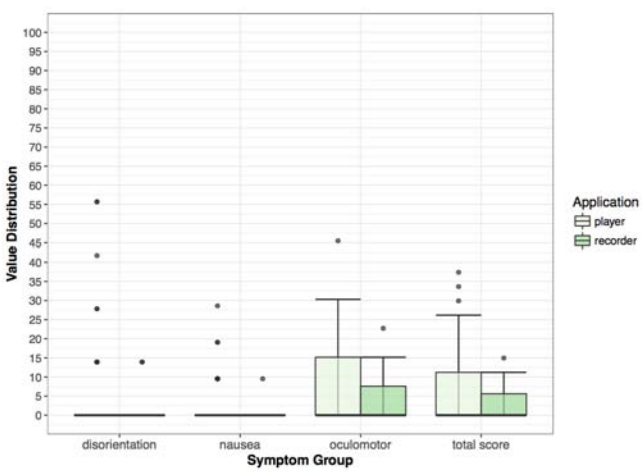

Figure 6. Simulator sickness scores for the medical trial comparing player and recorder

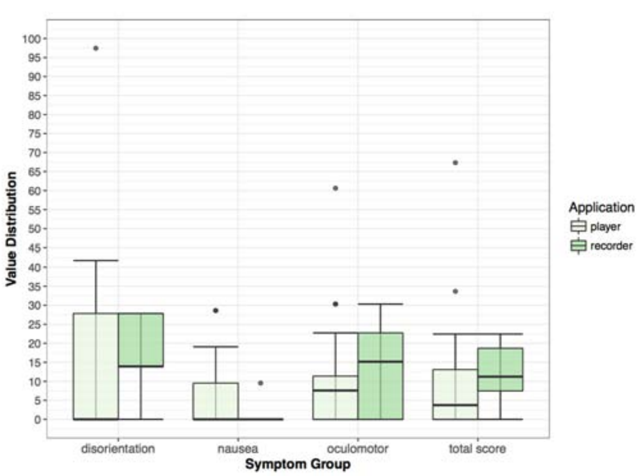

Figure 7. Simulator sickness scores for the space trial comparing player and recorder

DISCUSSION

In our experiment we found that there is almost no simulator sickness when using the Microsoft HoloLens, an untethered device that allows the user to move and interact hands-free with both augmented and real worlds. The most frequent symptom found was *eyestrain*, followed by headache and general discomfort. The least frequent ones were burping and vertigo. Kennedy et al. [18] state that the reported symptoms could naturally occur because of stress, boredom, or general fatigue. For the aviation and space trials, some of the participants arrived on site already in the morning, and were queueing for the experiment for 2-4 hours. In case of the space trial, the temperature in the waiting area in the hangar was very low, which may have contributed to some of the oculomotor symptoms found.

Symptoms of sickness can occur as a response to a sequence of unfamiliar movements (not experienced before) [16]. To account for this, the evaluation should consider contextual factors such as the body position in the room. In the *aviation* trial, subjects spent most of the time inside the plane, a good part of it in the cockpit, with body movement confined by its relatively small size. In the *space* trial, the experiment setup involved stepping on and off a small platform in order to install the Temporary Stowage Rack. In contrast, subjects of the *medical* trial performed the procedure sitting on a chair. This could explain the variation of disorientation, nausea and oculomotor related disturbances across all test beds. The two strongest symptoms for disorientation in the space case are *difficulty focusing* (24% slight or moderate) and *blurred vision* (21% slight or moderate). It may well be possible that this amount being higher than in the other two test beds (13%, 4% for medical vs. 9%, 7% for aviation) can be attributed to the platform setup.

Kolasinski [23] describes 40 factors related to simulator sickness that are grouped into three categories - individual, system and task related. As we think, the task related group contributes to simulator sickness in our trial, because it includes: *head movements* for that they increase susceptibility to simulator sickness [19, 32], which we have a lot (wearable device, looking for a virtual object within the workplace and size of a plane required you to be active in order to move on and proceed with a training), *method of movement* (potentially some of the movement inside the cockpit involved manoeuvring), *sitting vs standing* (sitting trial — medical vs. standing trial — space vs. sitting and standing trial — aviation).

The two applications differ in their complexity and approach: the recorder sets focus on the augmented world, as authoring is largely focused on adding virtual overlays on the real world. The player does the opposite, focusing on delivering guidance in the real world, coupled with interaction with physical objects (a probe or a stud).

The individual group is also seen as the one contributing to SS. *Concentration level* and *postural stability* for each person are different, and as we mentioned before, some of the participant were required to wait 2-4 hours for the trial to start. It is also worth mentioning that subjects may be under the influence of medication (such as β-blockers or birth control pills).

Our finding is that an eyestrain contributed to the simulator sickness the most (mean 0.28, SD 0.53), following by headache (mean 0.17, SD 0.43). For this evaluation, we did not investigate whether the headache may have been caused by the display or induced by the head-strap form factor. The SSQ instrument does, however, group eyestrain and headache together into oculomotor related disturbances, as the empirical data on which this grouping was based suggested that the nature of a headache is more likely caused by visual stimuli. With new devices, however, other explanations are possible for headache, too, including temperature of the working device, distance of the display to the eyes, optical quality of the lenses, weight and fit of the head-mounted display. Moreover, people differ physiologically and the device does not always fit to that. People also have different sensitivity to headaches. Investigating this further, it would be wise to ask participants about their experiences of discomfort caused by heat or straps or about the nature of their headaches.

Why choose AR training?

There are many advantages to simulator-based training in augmented reality besides its potential benefits for *competence-development* in situ, including: *safety* (it is secure to use the system, your hands are free and are in a full control of your working environment), *independence* from third party/training staff — potentially affecting self-esteem, the ability to teach special tasks remotely, *savings* of the resources required for training, and cost efficiency [38]. The biggest advantage of augmented reality is freedom of movement, while performing the training. Simulator sickness is one of the key issues to consider when determining to use an augmented reality head-mounted display. Despite the available information about potential positive effects, many industries are not rushing to integrate them into their operations. This paper suggests that one of the main concerns when using AR can be put to rest.

How to improve software and hardware?

The combination of a relatively wide field of view and all user interface elements being positioned within its limits created the sense of complete scene. A wider field of view would benefit both recorder and player applications. Software-wise, the navigation menus should be more consistently positioned, should be resizable, or should automatically adapt size to environmental context. When the user is examining something close up, all virtual content should automatically change its size and auto-fit itself into the designated field of view. A wider field of view would allow for a more seamless interaction with the physical world, overlaying, where needed, virtual content within a more natural field of view. This needs to be further investigated, as the existing literature [21] argues that there is little impact of the field of view on response time and mental workload, while our observations indicate that this may affect oculomotor comfort and disorientation negatively.

How likely are they to use AR again?

Due to lack of unpleasant symptoms or after-effects, users responded that they are likely to use augmented reality again. People who tried virtual environment simulators tend to be less susceptible to motion sickness, since they develop resistance to it. So, it is reasonable to say that if there is almost no SS during first experience with simulator, chances to develop sickness during subsequent sessions are small.

The current version of the player software applied in the trials was based on the idea that the user performs the task wearing the Microsoft HoloLens from beginning to end, with step-by-step AR guidance. AR-based training has the advantage of providing accurate information *where and when needed.* The prolonged use of an AR device may therefore not be a likely scenario in training. The possibility to work periodically with and without AR glasses would not only support the varying habits and preferences of the users, but also affect exposure to simulator sickness symptoms. The challenge for design in this case is that the user interface must adapt to non-continuous use scenarios. For example, easy access to relevant task phase guidance at any time should be provided.

Limitations

Our study cannot claim to generalise that augmented reality does not cause motion sickness. The scope of the experiment was to test simulator sickness for Microsoft HoloLens. It would be valuable to explore further whether other comparable smart glasses, such as the Meta-2 or the ODG R-9, are susceptible to motion sickness.

In addition, given that simulator technology has changed significantly over the past ten years, it may well be that the SSQ misses vital symptoms only caused by the novel devices or by applications not similar to flight simulators.

How to improve SSQ method?

We were aware of the specific characteristics of this widely used instrument before conducting the study. Nevertheless, in a review of all existing methods, we did not find a more appropriate method to meet our needs. SSQ is still widely used by the community in recent years (revaluation of the SSQ method done in 2013 suggests that is it still relevant [1]). The alternative FMS method introduced in [20] has unacceptable limitations for our case, where verbally rating the severity of MS every minute was not possible without intervening with the task execution. Moreover, direct observation methods can be more prone to subjectivity. SSQ was developed for simulators with both virtual and physical elements, i.e., for similar scenarios we face with mixed reality (other than fully immersive VR devices). Having conducted the study, we agree that the SSQ instrument could be extended and improved. For instance, it should have more questions about oculomotor related disturbances, as well as questions about user experience.

CONCLUSION

In this work, we empirically investigated simulator sickness in augmented reality training applications using Microsoft HoloLens. We found insignificant effects of simulator sickness. The main factor contributing to it is eyestrain, a symptom in the oculomotor group. We concluded that mixed reality interaction (spanning both the real and physical world) is less likely to cause simulator sickness than interaction with virtual elements alone.

Simulator sickness should be understood as a complex phenomenon, which differs from our everyday conception of motion sickness, often simply perceived as nausea. Based on our results, eyestrain can be seen as the most common and prominent symptom caused by using the HoloLens.

The symptoms observed appeared less frequent and milder than in comparable virtual reality simulators. Nonetheless, they cause discomfort to and affect technology acceptance of those selected few suffering of them. Innovation on how to alleviate these symptoms would certainly be beneficial to facilitate increase uptake.

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