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Human Performance and Cybersickness Evaluation of Mixed Reality Device for Immersive Assembly Simulation Training: A Case Study of Microsoft Hololens 2

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Abstract

A Mixed Reality (MR) device is an emerging technology that provides immersive training experiences. One example of MR technologies, offering high immersion, high interaction, and high information density, is the Microsoft HoloLens 2. This smart glasses device is classified as an Optical See-Through Head-Mounted Display (OST-HMD), which overlays augmented objects within a mixed-reality environment. However, the use of HMDs can lead to cybersickness, a condition that causes discomfort for users. This study aims to evaluate human performance and cybersickness symptoms associated with the HoloLens 2 during immersive training. The training task involved an augmented assembly simulation of an engine comprising six parts. The results indicate that using the HoloLens 2 as an assembly simulator significantly improved participants' performance and learning rate while minimizing errors. The device induced only mild cybersickness symptoms, including general discomfort, fatigue, difficulty focusing, sweating, difficulty concentrating, and blurred vision. Furthermore, the cybersickness assessment based on key factors revealed minimal symptoms, with scores of 3.98 for nausea, 6.32 for oculomotor effects, and 2.32 for disorientation. Based on the Simulator Sickness Questionnaire (SSQ) scoring matrix, the HoloLens 2 obtained an overall SSQ score of 4.48, categorizing its cybersickness symptoms as minor.

Keywords: Assembly Simulation Training, Cybersickness Evaluation, Human Performance, Immersive Training, Mixed Reality Device

1. Introduction

Due to technological advancements, various products and equipment have gained enhanced functionalities, increasing the complexity of their components. This rising complexity affects assembly difficulty, posing a challenge for operators to efficiently carry out the assembly process. [1]. During the assembly process, any error can be fatal and significantly impact the functionality of a product or system. [2] . Therefore, operators must adapt to the assembly process by enhancing their skills, knowledge, and experience through training. According to [3], training technicians is a process that must be carried out to improve operators' underlying skills (sensorimotor and cognitive) to adapt to new systems and technologies. One media training solution that can be applied to assembly operations is immersive training. Immersive training is a real-time simulation of an object, either physical or virtual, that allows multimodal interaction between objects and users to train cognitive skills and sensorimotor skills [3]. The existence of direct interaction between users and physical or virtual objects can improve user experience and make it easier to receive complex information [4]. This new technology that provides immersive experiences related to physical and virtual environments is called Mixed Reality (MR) [5].

Mixed Reality (MR) technologies combine virtual environments with the real world, enabling digital and physical objects to interact with one another. [6]. Based on a report from [5], MR technology was included in the top 10 ranked ICT (Information and Communication Technology) technologies in 2020. MR technology offers advantages over Virtual Reality (VR) and Augmented Reality (AR) by delivering high levels of immersion, interaction, and information. [7]. In terms of immersion, MR can be operated in real-time via spatial mapping for real-time and virtual merging [8]. Then, interaction in MR technology is related to the interaction between virtual and physical objects that can exist together (merged reality). The last character aspect involves information related to registration in 3D space, correlation to user space, and time persistence. The display tools in MR can be divided into 4 (four) categories: head-mounted displays, monitor-

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based displays, projection-based displays, and handheld display devices [9]. One such example of MR technology for head-mounted display-based smart glasses is the Microsoft Hololens.

Microsoft Hololens 2 is an MR technology released by Microsoft Corporation in 2016. This smart glasses technology is considered superior to conventional OST-HMDs (Optical See-Through Head-Mounted Displays) based on ergonomics, immersiveness, and friendliness parameters [10]. Furthermore, based on research conducted by [11] and [12], Hololens 2 has been proven to have a high level of accuracy, produce realistic 3D graphics, and have a high sensitivity. Therefore, Hololens 2 can increase work productivity in various sectors, such as manufacturing, engineering, construction, healthcare, and education [13].

The Simulator Sickness Questionnaire (SSQ) is an efficient and accurate questionnaire to measure users' cybersickness symptoms when interacting with a virtual environment (VE) via HMDs. The SSQ has been used more frequently in recent times to assess cybersickness [14]. The SSQ is well-suited for measuring both cybersickness and motion sickness in mixed reality environments, including those involving the Microsoft Hololens [15] [16]. The SSQ was developed by Kennedy et al. In 1993, the authors measured the cybersickness of pilots when operating a flight simulator [17]. Simulator sickness or cybersickness can be determined based on the SSQ score. According to [18], there are 3 (three) SSQ factors related to cybersickness with different weights of assessment: Nausea (9.54), Oculomotor (7.58), and Disorientation (13.92). Each participant will perform a self-report on their symptoms when interacting with virtual environments. The SSQ uses a 4-scale rating range from 0 (not at all) to 3 (severe). Assessment results are multiplied by each weighted factor. The total score was calculated by adding all subjective scores multiplied by 3.74 Equation (3).

This study measures the human performance and cybersickness felt by users using Microsoft Hololens 2 as a mixed reality device for 3D assembly simulation training. The engine type used as the object of assembly operation is the cylinder head component of Toyota's 1.6 Litre 4A-GE with 6 task assembly components: camshaft exhaust, camshaft intake, exhaust manifold, intake manifold, air filter, and cylinder head cover. It is hoped that mixed reality smart glasses device technology can be applied in the manufacturing industry to train technicians' psychomotor, sensorimotor, and cognitive skills. Thus, technicians and operators can enjoy an interactive, effective, immersive, and fun training atmosphere with low mental workload.

2. Methodology

This study involved 12 participants (9 male and 3 female) randomly selected with an age range of 18-26 years (young-adults age group). The profile of the participants involved in the experiment had an average age of 21.75 years old with a standard deviation of 2.86. There are 3 (three) participant criteria: 1) The participants had never used Hololens or other similar mixed reality devices, 2) The participants were not familiar with the cylinder head component of Toyota's 1.6 Litre 4A-GE, and 3) The participants do not have color blindness based on the results of the Zeiss online vision screening test.

Figure 1. Toyota's 1.6 Litre 4A-GE Augmented Engine and Components
Source: [19]

$$SUS\ Score\ (odd\ question) = x - 1,\ SUS\ Score\ (even\ question) = 5 - x \tag{1}$$

$$SUS\ Score\ = [(odd\ question\ result) + (even\ question\ result)] \times 2.5 \tag{2}$$

$$\begin{aligned} SSQ\ Score\ &= Average[(Nausea)(Oculomotor)(Disorientation)(Total\ Scores)] \\ &= Average\ [(9.54 * x)(7.58 * x)(3.74 * x)] \end{aligned} \tag{3}$$

*Note: x = participant assessment

The assembly simulation training using Hololens 2 was conducted in 20 iterations with one replication, with each iteration involving the systematic assembly of six parts. During the experiment, the researcher recorded assembly performance using two dependent variables: assembly errors and capturing errors. Assembly errors were calculated by measuring the sequence errors that occurred during the assembly process of the six components of the augmented engine. Meanwhile, capturing errors were measured based on synchronization discrepancies between the mixed reality device and the user. Each occurrence of an error was counted as a single error, and errors accumulated cumulatively. After the experiment, the participants completed the Simulator Sickness Questionnaire (SSQ) and the System Usability Scale (SUS) questionnaire.

The stimulus in this research was the augmented cylinder head component of Toyota's 1.6 Litre 4A-GE, which consists of 6 (six) parts: exhaust camshaft, intake camshaft, exhaust manifold, intake manifold, air filter, and cylinder head cover. This research utilized HEP64, an augmented assembly simulation training software developed by Axis 3D Technology Inc. and subsequently modified by the researchers. HEP64 software has 8 (eight) supporting features: profiler, hand ray, hand mesh, hand joint, record, engine puz, engine original, engine reset, and parts highlights. The profiler provides system and CPU performance information. The hand ray feature is used to point, direct, and select a target object using the hand from a long distance. The hand mesh feature displays a visual mesh of the hand in virtual environments. The hand joint feature displays the x-axis, y-axis, and z-axis in virtual environments. HEP64 software is equipped with a record feature to record all activities in merged reality. The next feature is the engine puz and the original engine, which can be used to explore the cylinder head components in terms of position, part names, and shape. The engine reset feature is used to repeat the assembly process after all parts are correctly assembled. The last feature is a highlight that provides information related to the assembly of target objects.

3. Results and Discussion

The evaluation of immersive assembly simulation training was based on two factors: human performance, measured by the learning rate, and the occurrence of cybersickness symptoms when using the Holol ens 2 device (Figure 2). The training consisted of 20 assembly iterations, which were categorized into four groups: the first five iterations (1–5), the second five iterations (6–10), the third five iterations (11–15), and the final five iterations (16–20).

Figure 2. Hololens 2 Device (Left) and Virtual Assembly Simulation Training (Right)
Source: Original image by the author

3.1. Human Performance Evaluation of Hololens 2 for Assembly Simulation

Measuring user performance and learning rate during HoloLens 2-based 3D assembly simulator training (Figure 2) was based on two dependent variables: assembly error and capturing error. Assembly errors occur when parts are incorrectly selected, picked, or installed during the assembly process. Capturing errors occur due to discrepancies in error detection and synchronization between user gestures and the HoloLens 2 during the assembly operation. Figure 3 and 4 shows the mean plot graph of the number of assembly and capturing errors for the five-iteration group.

The average assembly errors for the first 5 iterations, second 5 iterations, third 5 iterations, and fourth 5 iterations are 3.40, 0.35, 0.23, and 0.12, respectively (Figure 3). Based on the one-way ANOVA results, there was a significant difference in assembly errors among the iteration groups ($p < 0.001$). Consequently, Bonferroni post hoc tests were conducted to determine specific differences between groups. The first 5 iteration group showed a significant decrease in assembly errors ($p < 0.001$) compared to the second, third, and fourth 5 iteration groups. However, the decrease in assembly errors between the second, third, and fourth 5 iteration groups was not significant. Hence, assembly errors occurred frequently during the first five iterations because the participants engaged in trial-and-error learning while interacting with the mixed reality environments. Assembly errors can occur when a participant incorrectly selects and attaches a part to the main body of the cylindrical head component. Based on the researcher's observations, participants often ignore assembly procedures and instructions, so they try to find the assembly sequence of parts in their way. In addition, the participants were not attentive when distinguishing between the exhaust and intake camshafts in the first assembly trial. The two parts have the same shape and size but different ring-color characteristics.

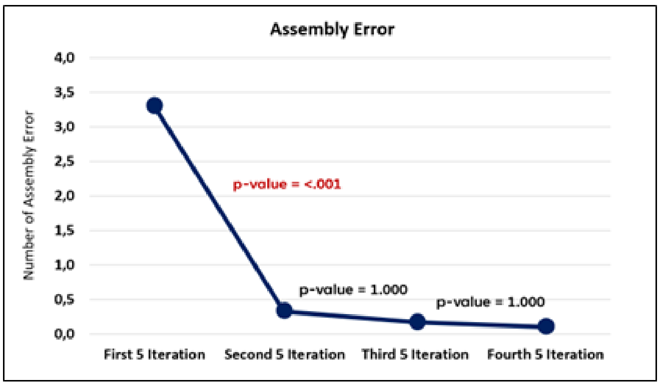

Figure 3. Graph Mean Plot of Assembly Error

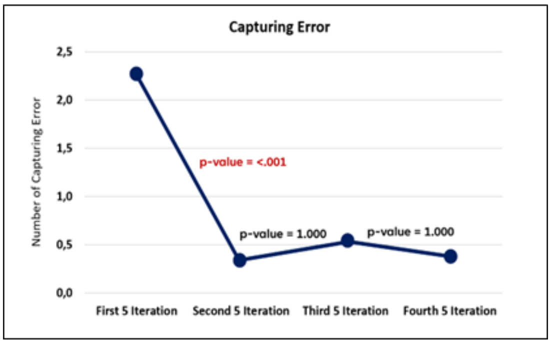

Figure 4. Graph Mean Plot of Capturing Error

The average capturing errors for the first, second, third, and fourth 5 iterations are 2.28, 0.30, 0.53, and 0.33, respectively (Figure 3). Based on the one-way ANOVA results, there was a significant difference in capturing errors among the iteration groups ($p < 0.001$), and Bonferroni post hoc tests were subsequently performed. The graph shows that the number of capturing errors decreased from the first 5 iterations to the second 5 iterations (Figure 3). The number of capturing errors then increased in the third 5 iterations and decreases in the fourth 5 iterations. A significant decrease in capturing error occurs in the first 5 iterations to the second 5 iterations. During the first 5 iterations, participants were still trying to adapt to interacting with mixed reality environments and gesture commands. Based on the researcher's observations, participants naturally use all fingers in a grasping motion when first interacting with mixed reality environments. The grasping movement was difficult to capture by Hololens 2, and participants often found it challenging to pick up augmented objects. As the number of assembly iterations increased, the participants adapted to gesture commands, thereby decreasing the number of errors. In the third 5 iterations, participants familiarized themselves with the interaction with the mixed reality environment but tended to be in a hurry, resulting in a capturing error.

This research proved that the participant's assembly performance increased based on the assembly and capturing errors. In addition, this study demonstrated the existence of a learning rate indicated by a decrease in the number of errors [20]. Therefore, the researcher conducted a Pearson correlation test on assembly error and duration with capturing errors to validate the learning rate. The output of the Pearson correlation shows that the assembly error has a very strong positive correlation (Pearson coefficient: 0.968) with capturing error. Thus, it can be concluded that the decrease in the number of assembly errors is also followed by a decrease in the number of capturing errors.

3.2. Cybersickness Evaluation of Hololens 2 for Assembly Simulation

Table 1. Experiment Data for the SSQ Symptom Factors and Scores

No	Participant	Nausea	Oculomotor Disturbance	Disorientation	Total Scores	SSQ Score
1	Participant 1	0.00	0.00	0.00	0.00	0.00
2	Participant 2	0.00	0.00	0.00	0.00	0.00
3	Participant 3	0.00	7.58	13.92	7.48	7.25
4	Participant 4	0.00	0.00	0.00	0.00	0.00
5	Participant 5	9.54	7.58	0.00	7.48	6.15
6	Participant 6	9.54	7.58	0.00	7.48	6.15
7	Participant 7	0.00	0.00	0.00	0.00	0.00
8	Participant 8	0.00	15.16	0.00	7.48	5.66
9	Participant 9	9.54	15.16	13.92	14.96	13.40
10	Participant 10	9.54	7.58	0.00	7.48	6.15
11	Participant 11	9.54	7.58	0.00	7.48	6.15
12	Participant 12	0.00	7.58	0.00	3.74	2.83
	Average	**3.98**	**6.32**	**2.32**	**5.30**	**4.48**

The cybersickness felt by participants when using Hololens 2 can be assessed using the Simulator Sickness Questionnaire. SSQ symptoms indicate three factors related to simulator sickness: Nausea, Oculomotor, and Disorientation [21]. In addition, there are 16 symptoms consisting of general discomfort, fatigue, headache, eye strain, difficulty focusing, increased salivation, sweating, nausea, difficulty concentrating, fullness of the head, blurred vision, dizziness (eyes open), dizzy (eyes closed), vertigo, stomach awareness, and burping [22]. Nausea is a symptom associated with digestive disorders, such as nausea, stomach congestion, salivation, and burping. Oculomotor is an indicator of visual symptoms, such as eyestrain, general discomfort, fatigue, headache, and difficulty focusing. Disorientation is a sign of symptoms related to body balance (vestibular) system disorders, such as dizziness and vertigo. Table 1 presents the experimental results related to the symptom factors and SSQ score.

During the data collection process, each participant wore a head-mounted display from a mixed reality device and performed an assembly training simulation while standing, allowing movement in a circular manner around the augmented engine. Upon completing the assembly training, participants were asked to conduct a self-assessment of their experienced cybersickness using the Simulator Sickness Questionnaire (SSQ). Table 1 presents the results of symptom factors, which include nausea, oculomotor disturbance, disorientation, total score, and SSQ score. An exemplary calculation of the SSQ score for Participant 3 is triggered by the presence of blurred vision symptoms, which are associated with oculomotor disturbance (one symptom) and disorientation (one symptom). Consequently, the nausea score is 0, the oculomotor disturbance score is 7.58 (1×7.58), and the disorientation score is 13.92 (1×13.92). The total score of 7.48 is obtained from the sum of two symptoms (oculomotor disturbance = 1 symptom and disorientation = 1 symptom) multiplied by 3.74. The SSQ score of 7.25 is calculated as the average of the nausea score (0), oculomotor disturbance score (7.58), disorientation score (13.92), and total score (7.48).

Based on the measurement of cybersickness using the SSQ, there were 4 participants who did not feel any symptoms (participant 1, participant 2, participant 4, and participant 7). Participant 3 experienced blurred vision caused by imperfect calibration of Hololens 2, so during the assembly process there were disturbances in the eyes and HMD. Participants 5, 6, 10, and 11 experienced eye strain and sweating. Eye strain can occur when participants focus on an object and then quickly move to another assembly object. Sweating is a normal condition because the experiment in assembly case for the augmented cylinder head component of Toyota's 1.6 Liter 4A-GE requires movement of the whole participant's body (hands, feet, head, and body). Participant 8 experienced symptoms of fatigue and eye strain during the assembly process. The highest SSQ score was found in participant 9 (13.40), who had symptoms of general discomfort and blurred vision. Subjects may feel uncomfortable when using Hololens 2, particularly on the head. In addition, participant 9 used thick glasses because of their significant nearsightedness, which affected their ability to use Hololens 2.

Based on the subjective assessment of 12 participants, Hololens 2 noted some light symptoms, such as general discomfort, fatigue, difficulty focusing, sweating, difficulty concentrating, and blurred vision. Cybersickness symptoms can be validated quantitatively. The SSQ score was 4.48 (below 5), which indicates negligible or minor symptoms of cybersickness [23]. This finding was confirmed by [15], who reported that Hololens as a training platform has negligible symptoms of simulator sickness for the user. Low cybersickness affects participant interaction in a mixed reality environment and the usability of using Hololens 2 for assembly simulator training.

In assessing the minor cybersickness of Hololens 2 for mixed reality device training, this study measured usability using the System Usability Scale (SUS) questionnaire Equation (1) and Equation (2), which involved 12 participants. The total average SUS score was 87.5 out of 100. According to the SUS scoring matrix assessment, Hololens 2 was classified as Grade A (Best Imaginable), so the use of Hololens 2 as an assembly simulator training can be considered feasible and acceptable. This finding is consistent with the research results reported in [24] and [25], in which Hololens 2 as a training device has excellent usability (acceptable). This study also conducted a Pearson Correlation test to determine the correlation between SUS and SSQ. SUS correlates (sig. 0.004) with SSQ, which is classified as a very strong negative correlation (Pearson coefficient: -0.758). Therefore, high usability positively influences users to experience low cybersickness symptoms.

4. Conclusion

The training object was an augmented assembly engine comprising of six parts. The human performance and learning rate were measured based on the assembly and capturing errors. When using Hololens 2 as an assembly simulator training, participants experienced a significant increase in performance and learning rate with minor errors. There was a very strong positive correlation between assembly and capturing errors. The Hololens 2 produces light symptoms that the user perceives: General discomfort, fatigue, difficulty focusing, sweating, difficulty concentrating, and blurred vision. However, Hololens 2 experienced negligible symptoms based on the cybersickness factor: Nausea (3.98), Oculomotor (6.32), and Disorientation (2.32). Based on the SSQ scoring matrix assessment, Hololens 2 obtained an SSQ score of 4.48, which is classified as a minor symptom of cybersickness. Based on the SUS score results, Hololens 2 had a total average SUS score of 87.5 out of 100 (Best Imaginable). Thus, technicians and operators can enjoy an interactive, effective, immersive, and fun training atmosphere with low mental workload.

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