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Evaluating the Effectiveness of Learning Design with Mixed Reality (MR) in Higher Education

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Abstract

Virtual Reality (VR) is being rapidly developed and bringing advancement in various related technologies through the virtual world. It has high potential and plays an important role in education and training fields. Mixed reality (MR) is a type of hybrid system that involves both physical and virtual elements. Whilst VR/ MR has proven to be an effective way to improve the learning attitude and effectiveness for secondary students, however not much work has been conducted on university students to compare the MR experience and traditional teaching approaches in learning design subjects. In this project, we investigated the effectiveness of students in learning design subjects with the support of MR. The effectiveness was measured based on their creativity and systematic approaches in design. Pre-tests and post-tests were conducted to measure the learning effects. We also compared the learning effectiveness of a student's study with the MR and traditional teaching materials. Nonparametric analyses were conducted to investigate whether the improvements were significant. Experimental results showed that after studying with the support of the MR technology, the students' abilities in geometric analysis (mean difference=4.36, $p<0.01$) and creativity (mean difference=1.59, $p<0.05$) were significantly improved. The students' ability in model visualization was also significantly better than the control group (mean difference=3.08, $p<0.05$). It indicated that the results were positive by using the MR to support their study. The MR was also better than using traditional teaching notes in various measured effects.

Keywords Virtual reality · mixed reality· extended reality · education · learning · HoloLens · university · design

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1 Introduction

The recent rapid development of Virtual Reality (VR) has led to the advancement of various related technologies through the virtual world. With the support of powerful computer hardware, software and networking, VR devices can be successfully deployed in various industries and with various widespread applications all over the world. Besides, VR development cannot succeed without widespread recognition by users around the world.

Mixed reality (MR) is a type of hybrid environment, where interactive virtual objects can be mapped to the physical environment, blending the real and the virtual. The recent advances in MR have high potential to play an important role in various fields, especially in education and training. Recent research has indicated that VR/ MR are effective in improving the learning attitude and effectiveness of secondary school students. Despite some studies being conducted to investigate the learning effectiveness of university students, not much work on university students has been undertaken to compare the MR experience and traditional teaching approaches in learning design subjects.

Learning design subjects is an educational process which involves a collection of learning activities for teaching students design subjects such as computer-aided design, computer-aided engineering, computer graphics, modelling, engineering materials, etc. The foundational key elements of the educational process include effective pedagogy, making use of appropriate tools and resources, time for teaching and learning activities, reflections from the learners, etc. (Laurillard 2013). According to the Learning Activity Design in Education Reference Model (LADIE 2005), learning design subjects can be categorized into the design and construction of learning activities (LAA) and the learning activity realization (LAR). MR is a new pedagogy which involves both learning content, and making use of effective tools for realization (Bidarra 2017).

Peña-Rios (2016) investigated the use of MR in distributed collaborative learning and evaluated students' learning experience at eight different universities in six countries. These research studies mainly focused on the online collaborative physical laboratory activities. Similar work has been done by Tang et al. (2018), however the learning effectiveness compared with traditional teaching materials has not been investigated. Therefore in this project, we aim to further extend our previous work by comparing the students experience with MR and traditional teaching approaches, and focus our study on creativity and systematic approaches in design. We address the following key issues in this article:

1. Investigate the effectiveness of students in learning design with the support of MR.
2. Compare the learning effectiveness with the support of MR and traditional teaching materials.

This article is organized as follows. In section 2, the current VR/ AR/ MR xR and its application in teaching and learning are reviewed. In section 3, we explain the recent MR technology and how it can be used to support teaching in design. Experimental results, including the background of the participants and outcomes, are summarized in section 4 and are discussed in section 5.

Finally, the proposed MR teaching approach, conclusions and future research are discussed in section 6.

2 VR and MR Technologies

The concept and functionality of VR has actually been developing over 80 years. The first multimedia device with a VR feature was invented and introduced for interactive theater experience for entertainment in 1957. Besides, the first VR device with a head-mounted display attached to a computer was introduced that enabled users with multi-sensory experience in a virtual environment. However, the hardware was extremely heavy and had to be attached to a suspension device. VR continued to be prevalent again in 1990's but the VR technology had slowed down and was less popular due to a lack of widespread applications and advancements in computer technology.

With the recent advancements in VR head gear designs, communication and computer technologies, it provides potential users in different fields a new VR experience which is more realistic and immersive for a wide range of applications in VR. Nowadays, the VR market has made significant contributions in various aspects, which range from academic research to engineering, sports, healthcare, design, military, education, construction and entertainment, etc. (Bates 2012). The potential application for VR entertainment is huge for the culture and entertainment industries, such as VR games, movies and animation (Jung et al. 2016; Molina et al. 2014). Further, VR technology in medical applications can also help improve today's distributed health care systems with high resolution medical consultation procedures and therapies (Riva 2014). VR technology has also been adopted in the military for combat and reaction training in dangerous situations (Lele 2013). VR can also be employed as a virtual training tool in many sports, etc. aimed at measuring athletes' performance, gestures, and skills as well as analyzing their techniques in sports training and games review (Bideau et al. 2010). With the aid of VR technology, product designers and engineers can create and visualize complicated 3D models and products using 3D modeling tools via web-based design and development processes for interactive and real time communication of product information (Jayaram et al. 1997). Furthermore, VR technology is commonly employed by construction and civil engineering contractors and consultancies for architectural and infrastructure design contractors during the planning and prototyping for design visualization (Whyte 2003). With the further advancements of the communication and computer technologies, the widespread uses of VR will be more popular in the future. VR not only enables experiential learning by simulating virtual environments but also supports dynamic forms of learning by creating artefacts in virtual environments with activities triggered by a learner's interaction (Dávidekováa et al. 2017). Leanne et al. demonstrated that VR is an immersive, engaging, comfortable, and interesting learning platform that has utility for team-based distance learning (Coyne (2018).

Augmented reality (AR) is a type of interactive, reality-based display environment that takes in the capabilities of computer-generated displays, sound, text and special effects to enhance the user's real-world experience (Caudell and Mizell 1992; Barfield 2016; Caudell and Mizell 1992; Azuma 1997; Neumann and Majoros 1998; Regenbrecht et al. 2005; Syberfeldt et al.

2017). AR combines real and computer-based scenes and images to deliver a unified but enhanced view of the world. AR can be employed to magnify the user's visual field with data and information under an instant real-world environment (Khan et al. 2011).

Mixed reality (MR) is a type of hybrid system that involves both physical and virtual elements. Many experts describe mixed reality as a sliding scale between a fully physical environment with no virtual elements, and a completely virtual environment (Barfield 2016). An explanation on MR was given in (Milgram and Kishino 1994) many years ago. It was described as a linear continuum, with fully real environments (reality) and fully virtual environments (virtuality) at either ends. The definition of the characteristics of MR is still valid many years later. An application of MR within the reality-virtuality-continuum has a higher share of real elements, e.g. virtual objects that reside in the real-world can be classified as AR. In contrast, e.g. physical objects integrated into the virtual world are referred to as augmented virtuality (AV). Despite the definition of MR evolving, it is still possible to observe the major characteristics of MR. Parveaua and Addaa (2018) classified MR into 3iV classes. First, it consists of both real and virtual content, and allows data contextualization. Second, the digital content is required to be interactive in real time. Third, the content needs to be spatially mapped and correlated to the 3D space.

The use of MR for simulated teaching and training is popular, and there is preliminary evidence of its instructional effectiveness (Ke et al. 2016; Hayes et al. 2013; Liarokapis and Anderson 2010; Hughes et al. 2005). Pan et al. (2006) explored the educational uses of a virtual learning environment (VLE) for collaborating on the issues of learning, training and entertainment using VR and AR technologies. The results indicated that the proposed VLE can enhance, motivate and stimulate learners' understanding of certain events that the traditional learning approach could not be achieved easily. Users can learn in a quick and engaging manner under the virtually entertaining environment. Nikolakis et al. (2004) presented an MR environment for 3D geometry education, in which the proposed system integrated three modules: Geometry Construction agent, a Collision Detection algorithm, and the Haptic Interaction agent. The user can give responses in the virtual environment using VR head gear for creating and visualizing various geometrical models with stereoscopic views. The results indicated that the proposed system can provide learners with a more efficient learning environment method. The potential use of MR can be widely adopted in education, from primary school to higher education levels.

Recently, the new technology of Extended Reality (xR) was implemented and adopted for engineering applications. This technology relates to all real and virtual combined environments and human-machine interactions generated by computer technology and VR head gear or hardware(s). xR integrates and collaborates with all the representative forms of AR, VR, MR, and augmented virtuality (AV) to provide a wide range of virtuality levels, from partial sensor inputs to immersive virtuality (Gownder et al. 2016; Berglund et al. 2018). However, little research work can be found on using xR for educational purposes.

3 Methods

In this project, we investigate and compare the learning effectiveness of students in design with the support of MR against traditional teaching materials. Lutters et al. (2014) proposed that the design of a product is characterized by the ability to balance between creativity and systematic approaches that employs problem solving and decision-making (Abramovici and Lindner 2013). Creativity is important in product design and can be found in many articles (Sascha et al. 2018). Systematic approaches in design refer to an ability in understanding the model and design. Creativity and systematic approaches are the essential skills and measurement means for designers. In this project, the learning effectiveness of students is measured by the level of understanding in three main assessment components in learning design: abilities in model visualization, geometric analysis and students' creativity.

3.1 HoloLens System

In this article, an MR application is developed on the HoloLens system, which completely self-contained, head-mounted holographic display. It can be used as a standalone handheld device to compute and perform real-time AR capabilities. HoloLens enables self-developed digital content or building models to overlay with a real environment, such as a wall, table or other objects. In addition, users can interact with the digital content in the HoloLens. It provides an immersive environment for users to explore the concept of reality and human perception in a real-time perspective. HoloLens can be applied in learning and education (Drexel 2018; Muller et al. 2018). For instance, in chemistry, a series of lessons has been designed to experience the structure of atoms and molecules. In biology, lessons can be designed to guide students in exploring structures, from the cellular level to organisms and human anatomy. In physics courses, the HoloLens can help students to uncover physical laws, forces, mechanics, electromagnetism, etc.

Figure 1 Hardware and configuration of the HoloLens

Figure 1 shows the hardware and configuration of the HoloLens (2018). The HoloLens (Figure 1) features a 1GHz custom-built Microsoft Holographic Processing Unit (HPU), 64 GB Flash memory, 2 GB RAM, optics and sensors units (HoloLens 2018). The optics unit includes 2 HD 16:9 light engines that project light through holographic lenses. The holographic resolution is up to 2.3 million light points. The high-resolution 3D digital content is projected by this unit. The sensors unit includes an Inertial Measurement Unit (IMU), 4 environmental understanding cameras, a depth camera, a video camera, microphones and ambient light sensors. The IMU measures the device's position and orientation, the environmental understanding camera provides environmental information to track the position of the head. The depth camera helps hand tracking and maps the spatial environment to allow interaction between the digital content and the real environment. The microphones allow users in providing voice input to signal the system with voice commands.

3.2 Application Development and Case Scenario

This project makes use of Unity (2018) as the game engine for application development. We also make use of Vuforia (2017) as the Software Development Kit (SDK) to enable the creation of the MR application that can recognize specified teaching material. This function is added to the developed HoloLens application because it not only helps to increase the engagement of the students, but the application can also be embedded in the teaching materials so that students are encouraged to explore the details on their own initiative. Figure 2 demonstrates that the digital content can be displayed in front of the user once the teaching material is recognized. We use C# as the programming language to develop the key features of the application.

Figure 2 Digital content displayed on the recognized teaching material.

In this research, an aircraft turbofan engine is developed for the students to visualize the three-dimensional (3-D) geometry of the digital model. The turbofan engine is employed as the case scenario as it consists of sophisticated structure and multiple components and is suitable for students in higher education. Students can learn the functions and explore the complex geometry of each component in the engine. The developed application satisfies three major characteristics of MR. First of all, the application enhances students experience in allowing contextual information to be exchanged. The digital model is displayed once the real teaching material is recognized. Secondly, the digital content can be interacted with in real time. The digital content can be signaled through gazing, hand gesturing, and voice command. A command manual is designed and is displayed at the bottom of the holographic screen for the students to signal the system in an alternative way. Thirdly, the contents are spatially mapped and correlated to the 3D space. Students can experience the digital model interacting with the real environment, for instance placing the model on the table and colliding with real objects.

Figure 3 The aircraft turbofan engine and command manual.

Figure 3 shows the developed turbofan engine and the command manual. Gazing and hand gestures are the key features in HoloLens for the users to interact with the digital models. In order to implement the instructions, students have to gaze on the targeted components and to act with core hand gestures, including air tap, drag and bloom in HoloLens (Figure 4).

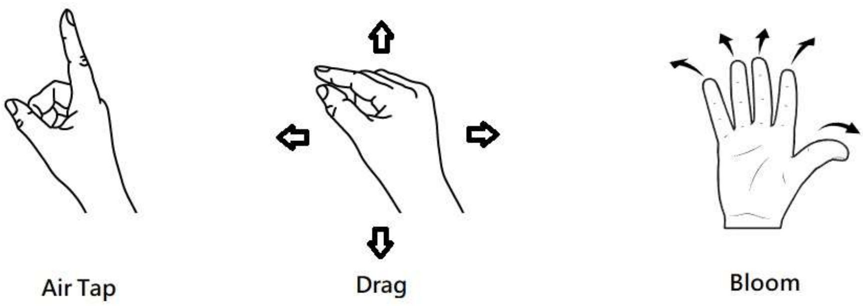

Figure 4 The core gestures of HoloLens used in the developed application.

The developed application allows students to view an exploded diagram and select the components of the aircraft turbofan engine. Students can select the components of the digital model individually through the command manual and voice instruction in order to look into the component in detail. The digital model can be hidden or transformed, including scaling, translating and rotating, so that students can explore its structure from different angles and perspectives. Mihaela (2013) suggested a student has to see (graphics, text), to hear (teacher's voice) and to experiment (practice or experience) what he/ she learns. Thus, when a component of the digital model is selected, a text description on the component is displayed, as well as hearing the voice navigation from the system at the same time. Students are not only able to experience the digital content, but also see the text description and hear the voice navigation in order to provide effective sensory input channels to enhance their learning. Figure 5 summarizes the command and instructions provided by the developed application for signaling the system.

Before examining the effectiveness of teaching design with the support of the MR technology by using the aircraft turbofan engine, we set up a pre-test to investigate the fundamental knowledge and skill sets of the students in the design field. The pre-test makes use of a car engine as the case study because it consists of complex geometry and multiple components with similar functionalities. The level of difficulty is also similar to that of the aircraft engine. The detail research protocol is described as follows.

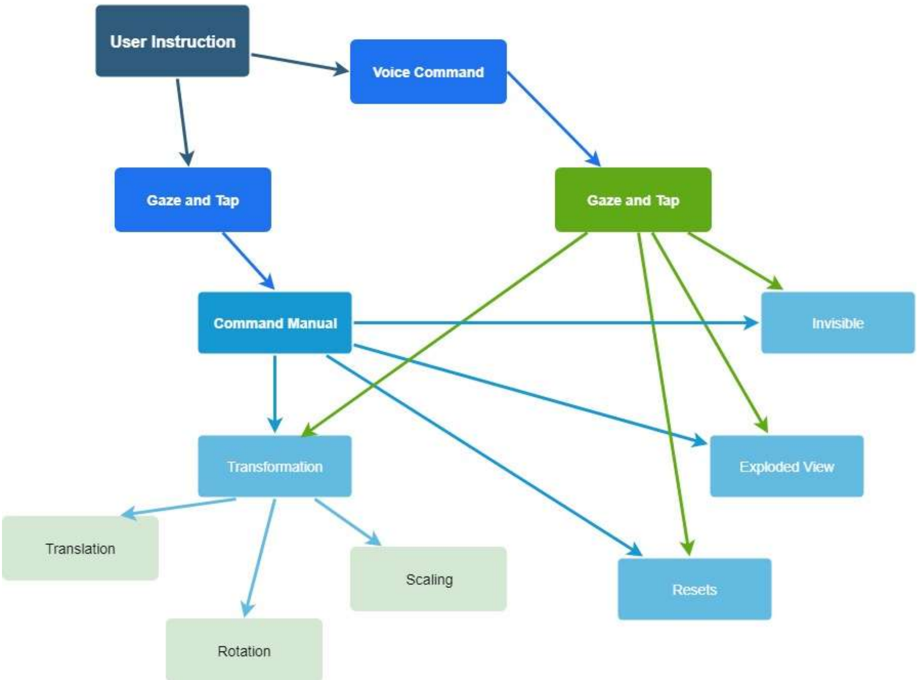

Figure 5 Command and instructions provided by the application.

3.3 Research Procedures

At the beginning of the investigation, two groups of students were recruited to participate in two different learning support materials separately. The experimental group learns design with HoloLens, while the control group learns design with traditional teaching material. The traditional teaching material consists of teaching notes which contain the same figures and content as the digital content in HoloLens. Due to the limitation of the traditional 2D teaching notes, students have less control on the viewing angles. In order to minimize the difference with the experiment group, a perspective view of the model is used in the teaching notes. The students were invited to participate in the investigation voluntarily and be randomly assigned into two groups. We measured students' abilities in learning design based on three main assessment components: model visualization, geometric analysis and student creativity.

Both groups of students were required to participate in the pre-test first to quantify their abilities in respect to a certain level of understanding in design. A car engine was used as the case study to set up the questions in the pretest. Students were required to answer questions related to the car engine model. Then, students learnt the product functions, features, geometry and design with their assigned learning support. For the experiment group, a 5–10 minutes briefing and experience sessions on the operation of HoloLens were given to familiarize with its operations. This ensured that the students can focus on learning design during the test without being distracted when operating the HoloLens. The post-test began after the students were familiarized with the HoloLens basic operations. Both groups of students were allowed to study the given turbofan engine and understand its function, geometry and structures for 10 minutes, with their preassigned learning support. Right after the learning session, a post-test with similar difficulty was used to assess the students' design abilities, as in the pre-test. Students were required to answer questions related to the turbofan engine model in the post-test.

The questions in the tests were set up based on the experience of the teachers. A preliminary rehearsal was also conducted to measure the test difficulty and duration. We decided to make use of nine questions for both tests, with 1 minute allowed for each question. The tests consisted of open-ended and multiple-choice questions.

3.4 Data Analysis

A commercially available statistical analysis package IBM SPSS (IBM 2018) was used for statistical analysis. Non-parametric tests were adopted to investigate the performance of the same group of target students. Despite student performance being measured based on the test scores, the marking schemes were still discretized based on the nature of the mainly qualitative questions used in the tests and the limited sample size. The Wilcoxon signed ranks test was adopted to compare the difference in the pre-test and post-test after studying with the HoloLens. To investigate student background and their abilities, the Mann-Whitney test was adopted to compare the experiment and control groups. A p-value of <0.05 is considered as statistically significant.

4 Results

This research was conducted in a local university in Hong Kong. A sample of $N=72$ students participated in this study voluntarily. The students were randomly assigned into two groups, in which $N_t=44$ (61.1%) students studied with the support of the HoloLens (experiment group) and $N_c=28$ (38.9%) students studied with traditional materials (control group).

Table 1: Participants characteristics and educational background

Variables	Experiment group	Control group
Mean age (year±SD)	22.56 ± 2.64	21.55 ± 1.68
Male	14 (48.28%)	17 (77.27%)
Female	15 (51.72%)	5 (22.73%)
1-4 Years of education	23 (79.31%)	22 (100%)
Postgraduate	6 (20.69%)	0 (0%)
Studied design	8 (27.56%)	10 (45.45%)
Didn't study design	21 (72.41%)	12 (54.55%)

Table 1 summarizes the characteristics and educational background of the participants. However, some students who did not complete their personal particulars completely were classified into the missing category. The sample was composed mostly of males (60.78%) in both groups, with a mean age of 22.1 years (SD = 2.29), in which most of the students had not studied related design subjects before. Figure 6 shows the respective faculty of the university students. It was found that most of the participants were studying in the Faculty of Engineering and the School of Design.

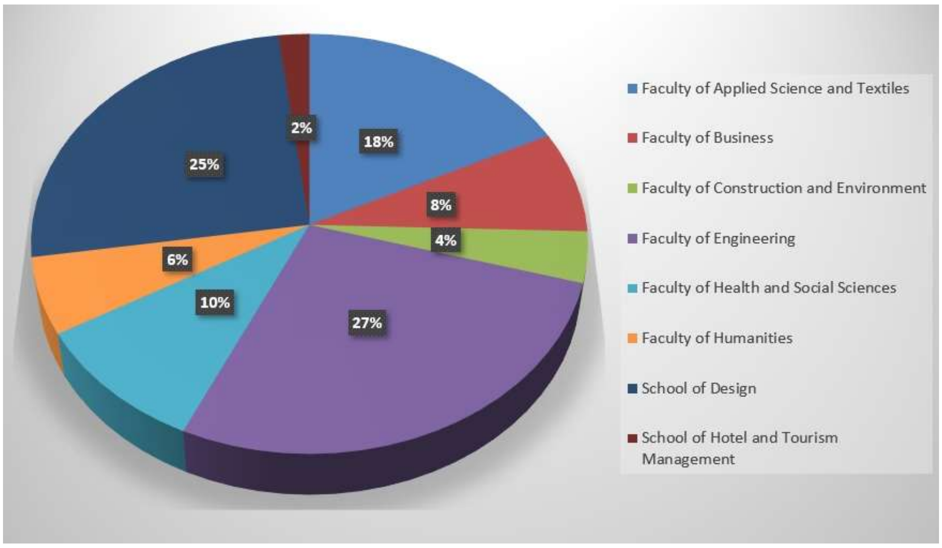

Figure 6 Studying faculty of the participants

Table 2: Students' design knowledge between the experiment group and the control group

Measures	**Experiment group *N*=44 Mean score (SD)**	**Control group *N*=28 Mean score (SD)**	***Z***	***p*-value**
Model Visualization	7.73 (7.43)	7.14 (7.13)	-0.301	0.764
Geometric Analysis	2.18 (4.52)	1.68 (3.33)	-0.261	0.794
Creativity	1.80 (3.42)	0.68 (2.86)	-1.564	0.118

Legend: (F) Mann-Whitney test; (p) Significance level; (*) p < 0.05; (**) p < 0.01; (***) p < 0.001.

Considering the knowledge differences in the design subject between the experimental and control groups, the Mann-Whitney test was conducted to investigate the abilities of students in three main assessment components. Table 2 shows that even though the experiment group got higher marks in model visualization (mean difference= 0.59, p=0.764), geometric analysis (mean difference= 0.50, p=0.794) and creativity (mean difference= 1.12, p=0.118). The p-values were >0.05, that means there were no significant differences in the students' background and abilities between the experiment and test groups.

After the students studied with the assigned learning support, they were asked to complete the post-test. The Wilcoxon signed ranks test was conducted to determine if there was any improvement in studying design with the support of the HoloLens. The positive difference represents that the mean scores of the experiment group are higher than the control group. Table 3 summarizes the students' abilities between the experiment group and the control group, and it was found that their skills in geometric analysis (mean difference=4.36, p=0.01) and creativity (mean difference=1.59, p=0.033) were significantly improved.

Table 3: Students' design abilities by studying with the support of the MR

Measures	**Mean difference**	***Z***	***p*-value**
Model Visualization	0.00	-0.017	0.987
Geometric Analysis	4.36	-3.422	0.01**
Creativity	1.59	-2.128	0.033*

Legend: (F) Wilcoxon signed ranks test; (p) Significance level; (*) p < 0.05; (**) p < 0.01; (***) p < 0.001.

The experiment group and the control group were compared to determine if there was any significant difference in ability in the assessment components. The Mann-Whitney test was applied to investigate the difference. The results in table 4 show that the experiment group got higher marks in all measures. However, the experiment group performed significantly better than the control group only in model visualization (mean difference=3.08, *p*=0.038).

Table 4: Students' design abilities between the experiment group and the control group

Measures	Mean difference	Z	p-value
Model Visualization	3.08	-2.079	0.038*
Geometric Analysis	0.831	-0.638	0.524
Creativity	1.32	-0.715	0.475

Legend: (F) Mann-Whitney test; (p) Significance level; (*) p < 0.05; (**) p < 0.01; (***) p < 0.001.

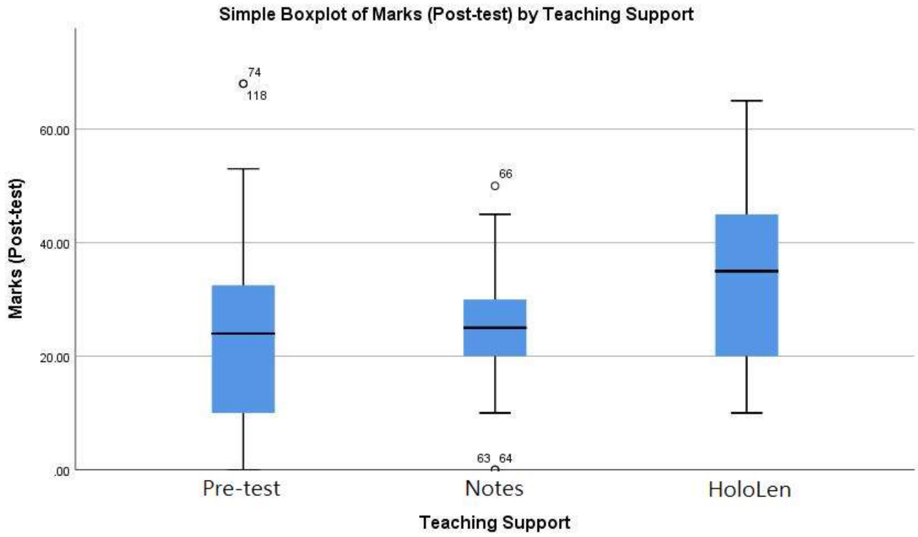

Figure 7 A boxplot of students' overall test performance studied with the support of the traditional notes and HoloLens in the post-test. Their performance was compared with the students' in the pre-test.

Finally, we compared the students' overall test performance with the support of the traditional notes and HoloLens in the post-test. A boxplot (Figure 7) was used to compare their marks in their pre-test. Their performance was also compared with the students' performance in the pre-test. The students' overall performance was calculated by the total marks of their measured design abilities. It was found that there were several outliers on the pre-test group and the students was studied with traditional notes. Although their medians were similar, the pre-test group showed a greater mark variability compared with the students who studied with notes. It implies that students have more consistent performance after studying with notes but the improvement was not significant, while the students who studied with the HoloLens showed a general improvement in their overall performance. By eliminating such data from the outliers, figure 8 illustrates the overall performance of each students' performance in the post-test against the time to complete the tests in a scatter plot. In this figure, the *x*-axis represents the students' overall performance in the post-test and the *y*-axis refers to the time difference for the students to complete the pre-test and post-test. A positive number means that a student spends less time to complete the post-test, thus making improvement. While a negative number refers to a student spending longer time to complete the post-test. It was found that most students (64.2%) spent similar or less time to complete the post test, in which 74.4% of them were the students who studied with HoloLens (blue dots). On the other hand, their overall marks were generally higher than the students who studied with traditional notes (red dots). Despite some students spending longer time to complete the post-test their performances were generally higher than those studied with traditional notes.

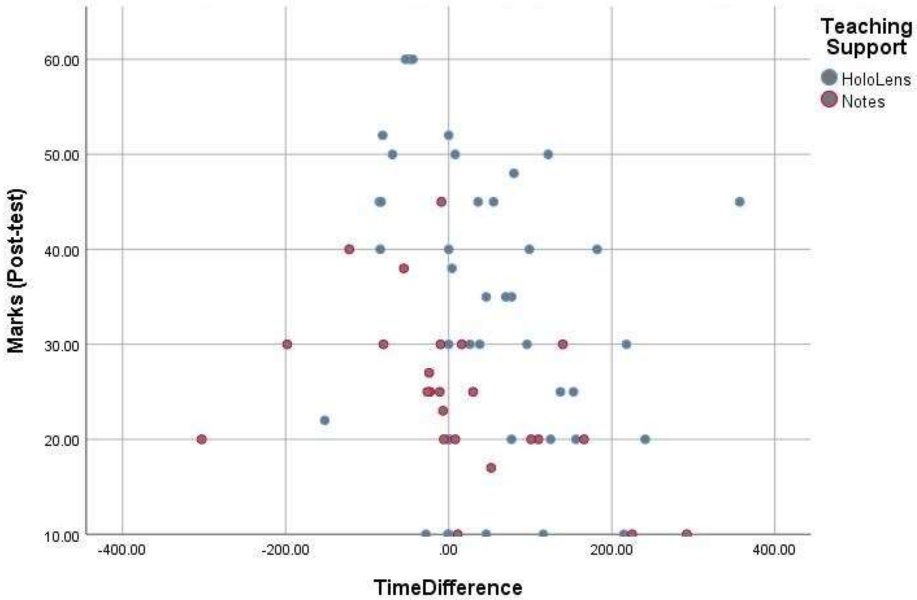

Figure 8 Scatter plot of each students' overall performance performed in the post-test against the time difference to complete pre- and post-tests

5 Discussion

Our study investigated students' abilities in learning design in higher education with the support of MR technology. Students were invited to participate in the study voluntarily. Regarding to the background of the participants, most of them had not studied related design subjects before. The students who did not study design from the experiment group and the control group were 72.41% and 54.55% respectively. It was suggested that even those students that did not have a strong background in design, they were still interested to learn with the aid of new VR/ MR technologies especially for the students from the Faculty of Engineering (27%), School of Design (25%) and Faculty of Applied Sciences (18%). Most of the participants were male (60.7%).

A pre-test was conducted to investigate the students' background in design, and it was indicated that student ability in model visualization was the highest (mean score=7.44) compared with their skills in geometric analysis (mean score=1.93) and creativity (mean score=1.24). This may be due to the highly conceptual theory in learning geometric analysis and training students' creativity in higher education. Therefore, further training and practice in these aspects should be considered. On the other hand, there was no significant difference in the measured abilities for the experiment group and the control group. That means the backgrounds of participants were similar at the beginning of the test.

After students studied with the support of the MR technology, their abilities in geometric analysis and creativity were significantly improved ($p<0.05$). However, only students' model visualization ability was significantly better than the control group ($p<0.05$). The results indicate that the turbofan engine model is difficult for most higher education students and more complex than a car engine. The traditional teaching materials are inadequate to help students visualize the models. MR is still an effective means for the students to visualize the model compared with the traditional teaching materials. Although the improvement in geometric analysis and creativity were not significant in the experiment group, both measured abilities were improved with the support of the teaching materials. On the other hand, students' overall performance was improved compared with the control group. Most students (74.4%) who studied with HoloLens spent similar or less time to complete the post-test and their overall performances were also generally higher than the control group. It is suggested that students' geometric analysis skill and creativity can be enhanced. Therefore, more support and training are still required for higher education students.

Although the positive effects of VR on students' learning design have been proven to be effective by numerous works (Radianti et al. 2020; Meyer et al. 2019; Allcoat 2018), few works can be used to verify the effect of using MR for learning design directly. We attempted to compare our results with existing publications, and the experimental results showed a positive implication on model visualization. This conclusion agrees with the results by Nisha (2019) that VR can enhance spatial design teaching and learning compared with traditional approaches. In addition, the overall performance and time to complete the test was improved in the experimental group, the results in line with those in Janabi (2019) and Wang and Dunston (2009), in which the test score and performance time were improved by using MR.

6 Conclusions and Future Research

Nowadays, VR/ MR has high potential and plays an important role in various applications, especially in the education and training fields. It is expected that VR/ MR related revenue will grow at a compound annual growth rate of over 50% in the next five years. The recent VR technologies have proven to be effective in improving learning attitude and effectiveness of secondary school students. The use of MR for simulated teaching and training is becoming popular, but the evidence of its instructional effectiveness is still preliminary. Design is one of the major studies in universities no matter in the Faculty of Engineering, Science and Design. It can be characterized by the ability to balance between creativity and systematic approaches that employ problem solving and decision-making. In this article, we investigated students' learning experience in their creativity and systematic approaches in design with MR, compared with the traditional teaching approaches. The developed application has three major MR characteristics: data contextualization, immediate interaction, and correlation to the 3D space. The turbofan engine was employed as a case study. The experimental results showed that with the support of the MR technology, students' abilities in geometric analysis and creativity were significantly improved, and were better than the control group in regard to model visualization ability.

Based on the preliminary findings on the measured abilities of the case study model, it is suggested that the MR experience can show a positive implication in the development of future case-based learning examples in design subjects. For the case scenario of a less complicated model, some features such as text description and voice navigation can be enhanced to facilitate students' skills in geometric analysis and in stimulating their creativity. For the case scenario involving a sophisticated model, blended learning approaches that combine both traditional teaching notes and interactive MR experience can be employed to assist in illustrating the complicated geometric relationships. On the other hand, MR experience showed a positive contribution to the overall student performance improvement, especially in their model visualization ability compared with the control group. We argue that visualization is one of the key factors for students' learning product design in higher education, which was supported by our research.

Despite learning design with MR technology showed positive effects in different design aspects, current findings are only based on a 72 sample size. By increasing the sample size, more findings and insights are expected. Besides, the current research did not focus on investigating the features of the developed application. In the future, more research, such as inviting students from different universities, and integrating the quantitative and qualitative survey, can be conducted in order to generalize the key features of the MR experience and content.

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