THE EFFECT OF INTERACTIVE MANUFACTURING WORK INSTRUCTIONS AS A TRAINING TOOL FOR ASSEMBLY TASKS

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This thesis is dedicated to my loving family:
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GLOSSARY

Augmented Reality (AR): “technology that allows the user to see the real world, with virtual objects super-imposed upon or composited with the real world” (Azuma, 1997).

Model-Based Definition (MBD): “MBD at its core, is a way of gathering and managing product/process data inside of a 3D model, in the form of annotations, parameters, and relations” (Alemanni et al., 2011).

Image target for AR system: “An image target is a normal image that is usually placed in front of a camera. This image will then be captured by the camera, after which the 3D model is placed on top of the image target” (Aziz et al., 2020).

ABSTRACT

In the current manufacturing industry, static work instructions (WI) are still widely used for manufacturing assembly training and they lack the dynamic information that interactive work instructions can offer. Augmented Reality (AR) training systems are receiving increasing interest in the scientific community, but there is a limited amount of research done on the long-term effect of the AR training systems compared with static training systems. This thesis study was done to investigate if interactive WIs such as AR WIs and 3D PDF WIs have an advantage on training efficiency and knowledge sustainability compared to static paper WIs. Within an experiment, it was observed that there are no differences between the three training methods when it comes to training efficiency, but AR WI proved to be more effective in sustaining the user's long-term recall precision than paper WI.

INTRODUCTION

Background

Assembly tasks are a core part of the manufacturing industry and many of its processes. According to Gonzalez-Franco et al. (2017), mass assembly lines for complex manufacturing heavily rely on robotized systems or highly skilled workers in modern manufacturing. In the era of Industry 4.0, digitalization and automation are becoming standard practice for various manufacturing processes (Kuper, 2020). Despite the increase of automation in manufacturing procedures, it is projected that manual industrial work will not disappear in the future (Fellmann et al., 2017). While automated assembly claims to be much faster and more accurate, manual assembly has more flexibility when it comes to changes in the production process. Manual assembly is especially beneficial when there is a high variance in production volume (Yoshimura et al., 2006).

In Deloitte's 2018 study on skills gap and future of work in manufacturing, it indicated that skill shortage is expanding, creating a gap between job vacancies and the pool of skilled workers capable of filling them. One of the reasons why is the retirement rate in the manufacturing industry. It is expected that more than 2.6 million baby boomers are to retire from manufacturing jobs over the next decade, and 2.4 million open jobs could remain unfulfilled in 2028 (Deloitte, 2018). Deloitte identifies the top reasons for this workforce concern as the:

- Shifting skill sets due to the introduction of advanced technologies
- Misperceptions of manufacturing jobs
- Retirement of baby boomers (Deloitte, 2018)

Deloitte (2018) further suggested that manufacturers should invest in developing training programs integrating digital technologies to help employees "move ahead on the digital curve" (Deloitte, 2018). This highlights the importance of a well-trained operator as well as effective training methods to ensure employee retention and high-quality products. Werrlich, Nguyen, and Notni (2018) indicated that the automotive industry is increasing in e-mobility and staff-fluctuations, requiring new workers to be constantly hired to match the growing production volume. Further emphasis is made on training materials for new workers to be "designed efficiently to ensure a good knowledge transfer whereby optimal process and product quality are guaranteed" (Werrlich et al., 2018, p. 297).

A Work Instruction (WI) in manufacturing is a guide for workers on how to perform an assembly task. It directs the workers to correctly assemble a product by showing the parts needed, proper procedures and rules to be followed (Servan et al., 2012). Traditionally, a WI is a paper-based document with simple two-dimensional drawings indicating how the product should be assembled. Static work instructions such as paper WI are still widely used within the industry and only a few companies are moving towards the implementation of interactive technology in the instructions. Engineers and operators are limited to using still images and textual instructions displayed on paper which often lacks the dynamic information that interactive instructions offer. Geng et al. (2015) pointed out that many manufacturing enterprises use two-dimensional static assembly instructions and 2D assembly drawing as means of assembly work instructions. They further argued that "2D assembly instruction cannot describe the assembly paths, assembly directions and assembly space clearly and accurately" (Geng et al., 2015).

The most common methods of assembly training in manufacturing are paper WIs and in-person training which requires a skilled employee on site. In the last decade, studies have proposed new methods of assembly training instructions and address the shortcoming of traditional methods. A study by Watson et al. (2010) observed that dynamic visualizations in work instructions yield faster assembly building times and fewer errors compared to static 2D instructions. In later years, studies focused more on investigating the advantages of novel assistive technologies such as augmented reality (AR) when used in assembly training.

AR-based training systems have received more and more interest in the scientific community over the last few decades. In the context of assembly training, many studies proposed AR training methods and investigated their advantages. Hořejší (2015) observed that AR instructions produce shorter assembly learning times in comparison with paper-based instructions. Büttner, Prilla, and Röcker (2020) investigated that AR assembly training is effective in preventing a mislearning of content over paper-instructions and in-person training. Gavish et al. (2015) found that there are fewer unsolved errors when using AR training methods compared to training with a video describing the assembly task. Aziz et al. (2020) observed that AR application learning method for a gold valve assembly provided a positive educational experience to the participants compared to paper-based learning method. While these studies highlight the advantages of AR applications, the visual assembly aids used in the AR applications usually involve a desktop display and tablet PCs. These AR delivery methods do not allow hands-free operation and divert the user's focus away from the assembly because it would require them to alternate between the task and the instructions (Evans et al., 2017). New devices that offer hands free, see-through Head Mounted Displays (HMDs) are becoming commercially available and are found to have advantages over other delivery methods. Funk et al. (2017) observed that using an HMD with AR information overlaid on physical assembly workspace reduces the error rate by 82% compared to paper-based work instructions and monitor-based instructions. Werrlich et al. (2018) claimed that HMDs can improve the quality and efficiency of assembly training tasks.

Significance

There are constraints in current comparative studies investigating the effectiveness of different methods of interactive assembly work instructions. Most of the newly proposed methods use AR assistive systems often compared with face-to-face training and paper manuals. These studies have limitations in that the use of AR instructions does not involve HMDs, which are known to have advantages over other delivery methods (Funk et al., 2017; Werrlich et al., 2018). Moreover, these studies are restricted in comparing AR instructions with non-interactive static instructions (e.g. paper manuals, monitor-based video instructions, tablet-based instructions with 2D images). This study aims to close this gap by comparing a HMD-based AR work instruction with a monitor-based 3D PDF digital work instruction involving animations and interactivity (toggling the models to pan, zoom, and rotate using a mouse), with paper-work instruction as a control variable.

Furthermore, many of the comparative studies are short-term, focusing on the learning curve and short-term retention of the users. While these short-term studies show that AR assistive systems can reduce errors and training time (Funk et al., 2017; Macallister et al., 2017; Werrlich et al., 2018), the question remains on if these training methods can be used in the long run. A study by Büttner et al. (2020) addresses this concern and conducted an experiment between face-to-face training, projection-based AR system training, and paper manuals to investigate the efficiency, short-term retention as well as long-term retention of participants when completing an assembly task. While the methodology of this study is noteworthy in investigating the long-term retention of the trained materials, there still lies a drawback in the chosen methods. The AR system does not involve an HMD, and the in-person training method requires a skilled trainer on site. This study aligns with Deloitte's (2018) suggestion on developing training programs integrating digital technologies, so an analog method such as in-person training is not considered in this comparative study.

Statement of Purpose

The purpose of this research is to study the effectiveness of two interactive work instructions as training methods when completing an assembly task. Specifically, it looks at how effective AR work instruction and digital 3D PDF work instruction are in terms of efficiency and long-term knowledge retention of the users, compared to training with a paper work instruction. This research tested graduate and undergraduate Purdue University students and industry professionals who were recruited on a volunteer basis on their ability to complete an assembly task after training with different methods. The final goal of the research is to determine if there lies a significant difference between the training methods when it comes to training efficiency and knowledge retention.

Problem Statement

In the current manufacturing industry, the demand exists for developing effective training methods integrating digital technologies to ensure employee retention and high-quality products (Deloitte, 2018; Werrlich et al., 2018). Static work instructions (WIs) such as paper WI are still widely used for manufacturing assembly training and they lack the dynamic information that interactive WIs can offer.

Augmented Reality (AR) training systems are receiving increasing interest in the scientific community and various short-term research projects have been done on investigating the effectiveness of AR-assisted assembly training. However, there is a limited amount of research done on the long-term effect of the AR training systems compared with static training systems. Moreover, there is not enough information on comprehensive studies comparing more than one interactive work instruction with static work instructions.

Research Question

How do the interactive work instructions and static work instruction compare in training efficiency and long-term knowledge retention when completing an assembly task?

Assumptions

The assumptions associated with this study are as follows:

- Participants will answer the pre-survey truthfully.
- Adequate time are provided for the training sessions.
- The 3D printed assembly model serves the same functionality as actual parts.
- No outside pressures affected participant performance while they completed the experiment.
- Participants will have the confidence of mastering the assembly at the end of the training phase.
- Participants in the AR instruction group will not feel physical discomfort such as motion sickness while utilizing the technology.
- Seven days between the initial training session and the evaluation session is an appropriate time space to test the participants' long-term retention.

Limitations

The following limitations of this study are outside the researcher's control:

- The AR training method will be using the Microsoft Hololens as the head-mounted display.
- 3D PDF work instruction will be delivered using a laptop computer.
- The participants do not represent the general population.
- The 2020 global pandemic will affect the sampling process of the participants.

Delimitations

The delimitations of this study are as followed:

- The learning curve of the participants will not be addressed, as cycle numbers of each participant will vary.
- An oil pump assembly will be the choice of assembly task in this experiment.
- The assembly parts of the oil pump will be 3D printed in PLA and TPU filaments.
- Participants are told that they will be compensated upon successful completion of all sessions.
- Subjects are restricted to Purdue University students and staffs at the Indiana Manufacturing Institute.

Summary

This thesis study addresses the limitations in current studies that examine the effectiveness of different interactive assembly training methods. Majority of current research on assembly training methods involving AR technology are short-term studies that do not prove the long-term use of the training method. Moreover, most of these studies compare AR methods with paper or face-to-face training methods. This study aims to compare AR WI and digital 3D PDF WI which also offers user interactivity, with paper WI to investigate the significance of the two interactive training methods compared to a paper WI.

LITERATURE REVIEW

This literature review section aims to support the research question stated in this thesis. The review focuses on identifying current industrial training trends, how augmented reality applications are being used in different industries, and the effects they have on the training outcome of the users. An extensive review was conducted to identify what current studies have been done on investigating the effectiveness of interactive methods of assembly training, as well as to examine the limitations in these comparative studies. Moreover, various domains that evaluate training methods are identified through current comparative studies, which will be applied in framing the methodology.

Industrial Training Trends

In various industries and will most likely increase in the future. Industrial training refers to providing individuals the working knowledge needed to achieve success in a real working environment. The 2019 training industry report provided by Training Magazine (2019) analyzed an online survey sent out in mid-2019 to U.S.-based corporations and educational institutions with 100 or more employees. The respondent profile was classified into more than 17 industries including manufacturing, technology/software, and educational services/academic institutions. The survey result on training delivery methods used in industries by company size indicated that most organizations are focused on using blended learning, instructor-led classroom, and online or computer-based methods. In terms of learning technology usage, 11 categories were identified, with learning management systems (LMSs) being the most used. A notable outcome of the report is that three new categories were added in 2019: Virtual reality at 9 percent, augmented reality at 6 percent, and artificial intelligence at 4 percent. Furthermore, the report wrote that large companies showed more willingness to experiment with these new technologies compared to small or midsize organizations. It is reported that 23 percent of large companies are using virtual reality, 11 percent for augmented reality, and 9 percent for artificial intelligence (Training Magazine, 2019). From the survey result, it can be assumed that the interest in novel technologies such as AR and VR has emerged

Manufacturing Training Trends

A report provided by The Manufacturing Institute (2017) analyzed trends that are remaking the manufacturing workforce. They have identified three major trends: 1) The fourth industrial revolution of manufacturing innovation is redefining how employees work, shop, and produce. More companies are expecting engineers to join the production floors with hands-on experience, and critical skills in manufacturing are quickly changing to address the increasing demands of the robotized and digitalized economy 2) skill needs are increasing in the industry, where more than 80 percent of manufacturers have reported skill shortages in production jobs 3) public-private partnerships are developing new training models. Internships and apprenticeships are opening doors for students to learn job skills to prepare for manufacturing careers. Earn-and-learn models are increasing, allowing workers to continue their education and join training programs after their employment to follow a path of lifelong learning (The Manufacturing Institute, 2017).

A more recent report by The Manufacturing Institute (2020) surveyed members in U.S. manufacturing companies to investigate how they are employing innovative training programs to address the current issues of the skills gap and employee retention. It is found on the survey that majority of the manufacturers focused on creating and expanding internal training programs to address the skills gap in the industry and giving more opportunities to current workers (The Manufacturing Institute, 2020). Moreover, manufacturers were further asked about the types of training that were implemented at their companies. It was found that the top choices were job-related technical skills training, cross-functional training, and new technology or equipment training. Every one of which affects directly on improving employee performance in their daily tasks. It was also found that the three-quarters of respondents indicated that training programs helps to improve employee productivity (The Manufacturing Institute, 2020). It is evident that the demand for technical training is growing in the manufacturing industry. The next section of the literature review will investigate how a novel technology like augmented reality (AR) has affected training and learning in various industries and in manufacturing.

Augmented Reality

Augmented reality (AR) technology has emerged in the last few decades and has been implemented as training and learning aids throughout various industries. According to Azuma (1997), AR is "technology that allows the user to see the real world, with virtual objects super-imposed upon or composited with the real world" (Azuma, 1997). As opposed to AR where graphical information is overlaid on objects in a real-life environment, virtual reality (VR) technology provides a completely immersive virtual environment. Many industries have shown their inclination towards implementing assistive technology such as AR and VR (Training Magazine, 2019), and studies have investigated how these technologies affect the training and learning outcome of the users.

History of Augmented Reality

The concept of augmented reality has been around for decades. The first notable AR technology was developed in 1968 when Ivan Sutherland, who is also known as the 'Father of Computer Graphics', created the first head-mounted display (HMD) connected to a computer to generate a simple cube visual with letterings (Peddie, 2017). Building off Sutherland's work, Steve Mann created the concept wearable AR, with wearable computers to generate visible electromagnetic radio waves that are naturally invisible (Peddie, 2017).

The term 'Augmented Reality' was first coined in 1990, by former Boeing researchers Thomas P. Caudell, and David Mizell who created an AR program that simplified the wiring instructions for aircraft assembly with overlaid diagrams onto physical parts (Caudell & Mizell, 1992). Then, the first functioning AR system was developed by Louis Rosenberg in 1992, who created 'Virtual Fixtures', that allowed the military to perform manual operations remotely (Rosenberg, 1993). AR technology has rapidly grown in the 2000's with the development of modern technology such as mobile devices. In 2004, the first AR system on a mobile phone was developed by researchers at the Bauhaus University (Möhring et al., 2004). The system allowed the detection and differentiation of different markers, providing rendered 3D graphics through a cell-phone screen.

Since then, AR technology had rapid growth in diverse areas including manufacturing. Airbus has used a Mixed Reality Application (MiRA) that provides an AR program displayed on a tablet that overlaid part information as well as virtual 3D mock-ups to assist production line workers to check the integrity of the aircraft they are developing. It was proved that the MiRA significantly reduced the time needed to inspect the product parts from three weeks to just three days (Hand, 2019).

Augmented Reality vs. Virtual Reality

Augmented reality (AR) is often confused with virtual reality (VR), but they have a significant difference when it comes to their application method. Farshid, Paschen, Eriksson, and Kietzmann (2018) define virtual reality (VR) as “complete, 3-D virtual representations of the actual world or of objects within it” (Farshid et al., 2018). VR technology allows users to put on a headset where they are completely immersed in a virtual world, whereas AR technology displays overlaid digital content on the real world through eyeglasses. In Hand’s (2019) words, AR takes the existing physical environment and “adds digital information to it to create the augmented environment”.

AR in Assembly Training

In the context of manufacturing instructions and training, many systems using assistive technology such as AR have been proposed over the few decades. This particular technology can be delivered in a myriad of forms such as a smart phone display and wearable smart glasses. Billinghurst and Schmalsteig (2002) proposed using mobile phones to give AR assembly instructions, and Hořejší (2015) proposed a system using a conventional web-camera to shoot the workplace environment with AR information displayed on a monitor placed in front of the worker. However, with the introduction of head-mounted displays (HMDs) over the recent years, more studies are focusing on using HMDs and in-situ projections.

There are existing studies that examine the effectiveness of assistive technology focusing on the training aspect of manual assembly, shifting away from traditional methods (e.g. paper manual, face-to-face training). Most of the recently proposed assistive training systems create augmented reality environments using in-situ projections (Büttner et al., 2020; Funk et al., 2017) or HMDs (Werrlich et al., 2018). According to Tang, Owen, Biocca, and Mou (2003), using an

HMD with AR information overlaid on physical assembly workspace reduces the error rate by 82% when performing an assembly task.

A research study by Werrlich et al. (2018) focuses on evaluating the training transfer of HMD based training for assembly tasks. The authors argue that comprehensive evaluation of using HMDs com AR technologies is still very limited despite the growing attention of the tool by the scientific community. Their goal was to close this gap by conducting a user study comparing the effects of two different HMD-based software modalities, both using the Hololens, for manual assembly training tasks. This between-subjects study consisted of 30 participants who were assigned into two groups with no significant experience difference in assembly. Both groups assembled an engine four times to complete a tutorial, beginner, intermediate and expert level with varying amounts of information. After finishing each level, participants were asked to repeat the assembly task without any assistance. The second group was assigned to take an additional quiz level before assembling without the assistive system. The results indicated that group 2 made 79% less sequence mistakes compared to group 1. The authors claim that "a learning phase where trainees have to pass a final examination before proceeding with the real assembly tasks without any assistive system, helps to improve the training transfer" (Werrlich et al., 2018). Another notable argument by the authors is that a slower completion time can help to increase the quality of the assembly.

A study by Büttner et al. (2020) proposes a projection-based AR system in an assembly training instance to investigate how people learn with three different types of instructions: AR assistive system, personal training, and paper manual. The researchers claim that there are limitations with existing research of assistive systems as they mainly deal with short-term studies, and they raise the question of whether such systems can be used in the long run. Their between-subjects experiment design focuses on investigating the training efficiency and knowledge sustainability of each training system with 24 participants (7 assigned to the paper condition, 9 to the AR condition, and 8 to the personal training condition). Data collection process for each training system was over four sessions: One pre-test session, two training sessions and one evaluation session. The participants were asked to assemble a commercial construction kit consisting of 24 parts in 23 steps. The results of this study revealed that personal training method has the best training efficiency. The use of AR system does successfully prevent a mislearning of content like personal training, but it lacks efficiency in terms of learning speed.

As for knowledge sustainability, their study shows that "once an assembly task is properly trained, there are no differences in the long-term recall precision, regardless of the training method" (Büttner et al., 2020). This is especially notable because the fourth session that takes place a week after the initial training session to test long-term recall did not show any differences between the groups.

Peniche et al. (2012) also explores the effectiveness of assistive technology by combining both virtual reality and augmented reality to improve the mechanical assembly training process. The authors claim that virtual reality as itself has a limitation as a training tool because training in an immersive environment does not necessarily mean the acquired skills can be successfully transferred into completing real assembly tasks. Moreover, the authors stated that conventional training method (training with physical parts from the start) are not applicable when tasks involve risk or danger. The proposed training process consists of two stages, where a participant would first use a virtual reality system to learn a portion of the training process and move on to the next stage where they would train with augmented reality with direct contact with the mechanical assembly (in this case, a milling machine). The study consisted of a control group that goes through a conventional method and an experimental group that uses the proposed AR/VR system. The participants were instructed to go through the training five consecutive times, and the amount of time it took for each cycle was recorded. The authors investigated the learning curve of each group, revealing that the proposed AR/VR system is as effective as the conventional method of training with real assembly models (Peniche et al., 2012). This research design has limitations in evaluating knowledge sustainability of the participants. The experiment is conducted over one day, which does not provide enough data to investigate the long-term recall of the participants.

AR in Education

Existing publications have studied the effects of AR on different educational settings. Von Jan et al. (2012) studied the application of AR in medical education and found that AR-assisted learning significantly enhances the learning process for graphical subjects in medical education. Furthermore, the authors found that AR-assisted learning captures the learners' attention because it provides more interactivity compared to conventional teaching methods (Von Jan et al., 2012). Di Serio et al. (2013) showed that AR technology has a positive impact on the motivation of middle school students in a visual art course. Students were able to achieve high levels of concentration and engagement throughout the course, compared to a traditional learning environment (Di Serio et al., 2013). While these studies focused on user interactivity, other studies have addressed the impact of AR in knowledge retention of the learners. Perez-Pérez-López and Contero (2013) presented a case study of using an AR application to support the learning and teaching process of anatomical structures at the primary school level. Results showed that students using the AR application retained more information than those in a traditional learning environment (Pérez-López & Contero, 2013). As discussed above, AR applications have been used in various fields of knowledge and in different academic levels.

AR in Medical Training

Other notable studies regarding AR capabilities can also be found in the field of medical training. A study by Ropelato et al. (2020) examined the use of AR headsets and AR surgical simulations to train physicians in microsurgical skills. Participants went under two training sessions and results showed that participants training with the AR simulations had improvements in performance compared to ones with classical training (Ropelato et al., 2020). Dickey et al. (2016) conducted a pilot study to investigate the potential deployment of AR-assisted surgery application in urology. Urology trainees and faculties were volunteered to experience the application in an operative setting and were asked to give a feedback survey. Results showed that 81% of the participants want this technology in their residency program, and 93% indicated that they would see AR-assisted surgery application in the operating rooms in the future (Ropelato et al., 2020). The studies mentioned above shows that AR applications can be applied in training medical professionals and potentially used in assisting real-time surgery.

Advantages of Instructional Animations

A publication by Höffler and Leutner (2007) investigates the instructional effectiveness of animations compared to static pictures on learning outcomes by conducting a meta-analysis of 26 studies, deriving 76 comparisons of dynamic and static visualizations. The authors found evidence that animations yield advantage over static pictures under specific instances of instructional situation. Their outcome indicated that animations are superior to static pictures when “the depicted motion in the animation explicitly refers to the topic to be learned” (Höffler & Leutner, 2007). However, animations are not superior to static pictures when the visualizations are used for decoration purposes instead of representational. Moreover, the study showed evidence that animations have a significant advantage for acquiring procedural-motor knowledge or the ability to replicate the procedure (e.g. assembly instructions; “trained capability to reconstruct a machine gun” [Spangenberg, 1973]).

Building off of Höffler and Leutner (2007)’s analysis, Watson, Butterfield, Curran, and Craig (2010) presented a study to evaluate the effectiveness of an instructional animation in an assembly task instance. Their main goal was to answer the research question: “Are instructional animations more effective than static representations (text of diagrams) as an instructional format for assembly tasks?” (Watson et al., 2010). Their experiment consisted of 30 participants, equally and randomly assigned among three instructional groups: Monitor-based text instructions, monitor-based diagram instructions, and monitor-based animated instructions. Participants in each group were assigned to complete a self-paced assembly task daily over five consecutive days. The assembly model consisted of 49 separate parts, and 33 procedural steps for the assembly task. The authors focused on collecting the overall build time, reference time, and net build time of each instructional group at each build. In addition, number of errors and number of references (events unrelated to instructional format). Results indicated that the mean build time (five builds each) for the Animation group was 56% faster than the Text group and 28% faster than the diagram group, providing evidence that animation instructions result in faster assembly build times. Moreover, the error count of the animation group at build 1 had considerably lower number compare to the other two groups, suggesting that animation instructions generate more consistent and error-free build times.

The effectiveness of animations mentioned above can be connected with the various comparative studies mentioned throughout this section. In the words of Webel et al. (2013), humans attain most of the information through their eyes so the “visualization of information is vitally important for developing efficient training systems” (Webel et al., 2013). AR systems offer dynamic animations in the form of holograms laid over the physical workspace, allowing users to be spatially aware of the work environment without having to refer back and forth to the instructions.

Evaluation of Training

When testing a training module, the question arises: How do we measure the effectiveness of training? From various comparative studies of training methods, researchers most often identified efficiency(Büttner et al., 2020; Hořejší, 2015; Watson et al., 2010), knowledge retention (Büttner et al., 2020; Pérez-López & Contero, 2013), and learning curve (Peniche et al., 2012) as their variables in determining the effectiveness of training. This section will focus on defining what these domains entail.

Efficiency

Clark et al. (2006)'s cognitive load theory defines efficiency in two variables, learner performance, and learner mental effort. In their words, "instructional environments that result in higher learning outcomes with less mental effort are more efficient than environments that lead to lower outcomes with greater mental effort" (Clark et al., 2006). It is written that the efficiency of an instructional product can be quantified referring to the efficiency metric. An efficiency metric is calculated by deducting the mental load from performance outcomes. In the metric, high efficiency is determined with high level of performance and low mental effort. In contrast, low efficiency is represented with low level of performance and high mental effort.

In previously reviewed literatures, comparative studies on different training methods quantified the efficiency of the training methods by measuring the training time used to complete the training, and the errors that occurred in the performance of the trained materials.

Knowledge Retention

Recent publications regarding the effect of learning conditions on user knowledge retention have been reviewed. Shail (2019) claims that "the process of rehearsing the material creates stronger neural networks connections within the brain and conveys the memory from short-term to long-term" (Shail, 2019), emphasizing that the retention percentage is improved by repeating a task multiple times over a period of time.

A study by Rondon, Sassi, and Furquim De Andrade (2013) compares a computer game-based learning method with a traditional lecture-based learning method as a means of teaching anatomy and physiology to undergraduate medical students. The research objective is to examine the learning gains and knowledge retention of the students when taught with different learning conditions. Both short-term and long-term knowledge retention data was collected by instructing the students to complete a pre-test to investigate their prior knowledge, a post-test conducted immediately after learning to assess short-term recall, and a long-term post-test conducted six months after learning to assess long-term recall. The results indicated that the computer-based learning method is comparable to the traditional method in terms of short-term knowledge retention, but traditional lecture proved to be more effective in the student's long-term knowledge retention (Rondon et al., 2013).

Rondon et al. (2013)'s findings on long-term knowledge retention aligns with Büttner et al. (2020)'s results. Both studies concluded that digital interactive learning methods (projection-based AR system (Büttner et al., 2020), and computer game-based learning system [Rondon et al., 2013]) do not have an advantage over analogue methods (personal training [Büttner et al., 2020], lecture-based learning [Rondon et al., 2013]) when it comes to long-term knowledge recall.

Jeske, Schlick, and Mütze-Niewöhner (2014, as cited in Pimminger, Neumayr, Panholzer, and Augstein, 2020), argue that instructional forms play a minor role as they are only relevant for the first assembly executions. In other words, the more a person repeats the assembly steps, the more irrelevant the instructional method becomes.

Summary

In conclusion, industries are more focusing on training methods that involve novel technology such as AR. AR tools as learning and training tools have been explored in various industries such as education and medical training. AR applications in these areas have proved to have advantages in improving users' motivation and engagement in learning, and in training of medical surgeries. Comparative studies on identifying the effectiveness of AR in training of assembly tasks have been reviewed, and well as the limitations of these studies. Very few studies included HMDs as a delivery tool, which is known to yield less errors when completing an assembly task. Moreover, the existing comparative studies mainly investigate the learning efficiency and short-term knowledge of the training methods. This section of the thesis identified these gaps in current literature and further detected the evaluation domains of training.

METHODOLOGY

This section introduces the research methods that will be used to collect data for this study. The purpose of this chapter is to describe the research type, research question, hypotheses, variables, the samples that were taken, the data that were collected as well as how they were analyzed.

Research Question

The study addressed the following research question: How do the interactive work instructions and static work instruction compare in training efficiency and long-term knowledge retention when completing an assembly task?

Hypotheses

The proposed hypotheses were defined to investigate the training efficiency (H1 to H3) and knowledge retention (H4-H6). Taking the results of Funk et al. (Funk et al., 2017) into consideration, the researcher assumed that assembly tasks are learned faster with the AR WI compare to the paper WI. However, the researcher assumed that it cannot reach the training efficiency of the 3D PDF WI, since the 3D PDF file displayed on the laptop screen is more intuitive to the users since the AR WI integrated with an HMD is a novel concept. Regarding knowledge sustainability, the researcher assumed that information that is displayed with spatial awareness leads to greater memorability compare to static images in a paper WI. The framework of the hypotheses adopted Büttner et al. (2020)'s research study of comparing three types of training methods for assembly training (Büttner et al., 2020). The hypotheses were as followed:
H1: Assembly tasks are learned faster with a digital 3D PDF instruction than with a paper work instruction.
H2: Assembly tasks are learned faster with an AR work instruction than with a paper work instruction.
H3: Assembly tasks are learned faster with an AR work instruction than with a digital 3D PDF work instruction.

H4: An assembly task trained through a digital 3D PDF work instruction is better remembered than one trained by a paper work instruction.
H5: An assembly task trained through an AR work instruction is better remembered than one trained by a paper work instruction.
H6: An assembly task is remembered equally well, regardless if it is trained through an AR work instruction or through a digital 3D PDF work instruction.

Variables

The variables for the study are outlined in the table below (table 1).

Table 1. Study variables and their categories.

Independent Variables	Dependent Variables	
	Training Efficiency	Knowledge Sustainability
Paper group (Control)	Number of required training cycles in session 1	Number of errors occurred after one week
AR group (Experimental group 1)	Required training time (seconds)	
3D PDF group (Experimental group 2)	Number of errors occurred after one day	

Sampling

The target population of this study is Purdue University affiliates over the age of 18 who have no underlying conditions that would prevent them from using the AR head-mounted display. To gather the samples within the given time frame, recruitment flyers were created and posted around the Indiana Manufacturing Institute (IMI) facility. The reason for this is because the IMI allows the recruitment of participants from different backgrounds and grade-levels as the facility has diverse foot traffic of Purdue University affiliates.

Recruitment

As mentioned above, recruitment flyers were created and posted around the IMI facility. Additionally, a recruitment email with the flyer attached was sent to the IMI staff email list to maximize participant recruitment. The recruitment email was distributed by the facility manager of the IMI. The flyer content included the study title, purpose of the study, general description of the study, researcher contact information, IRB protocol number and a QR code that leads to an on-line link to a Qualtrics screening, and a link that leads to the sign-up website. It was also written that the participants will be entered into a raffle where the researcher will give out five $20 Amazon.com e-gift cards.

Screening

Since the study utilizes AR technology, a participation screening was mandatory for any potential participant interested in taking part of the study before signing up for time slots. The screening was created with Purdue Qualtrics, asking them three questions: 1) ‘Do you carry a medical device such as a pacemaker?’ 2) ‘Are you prone to motion sickness or cyber sickness that might prevent you from using an augmented reality headset?’ 3) ‘Do you have a history of a seizure or epilepsy?’. If the person had selected yes in any of the questions, a prompt appeared that they do not qualify to participate in the study. These screening questions were based on the health and safety information of the Microsoft Hololens official website.

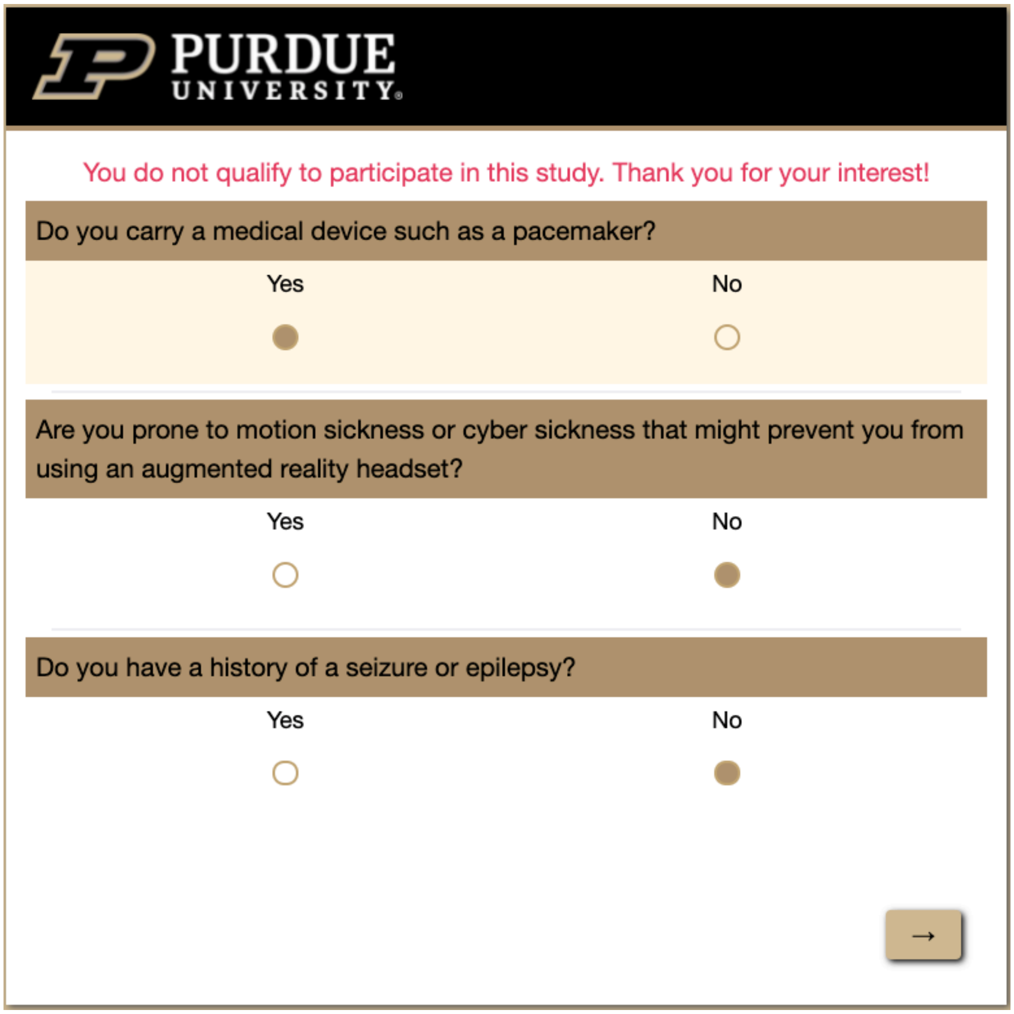

Figure 1. Screenshot of the Qualtrics Screening

Development of Work Instructions

In this research study, three different types of assembly work instructions were created: Two interactive digital work instructions and one static work instruction.

Digital 3D PDF WI adopted Hartman, Kozikowski, Thiyagarajan, and Yun (2019)'s model-based WI template as shown in figure 2. The digital document is created by using Anark Core's in-depth publishing functionalities. The CAD assembly model, BOM data, and BOP are uploaded to the software from a local drive. Animations were created within Anark Core as well as PMI and textual instructions. Participants could access the 3D PDF work-instruction via a laptop display. Each instruction step had a corresponding 3D assembly animation with textual information which can be paused and re-played. Participants were also able to toggle with the 3D model to pan, zoom or rotate.

2D Paper WI (fig. 3) was created by printing out each step of the digital 3D PDF. The graphics of the assembly were created using Anark Core, a publishing software. Participants were able to physically navigate through the instruction presented in a hard-copy, booklet-form.

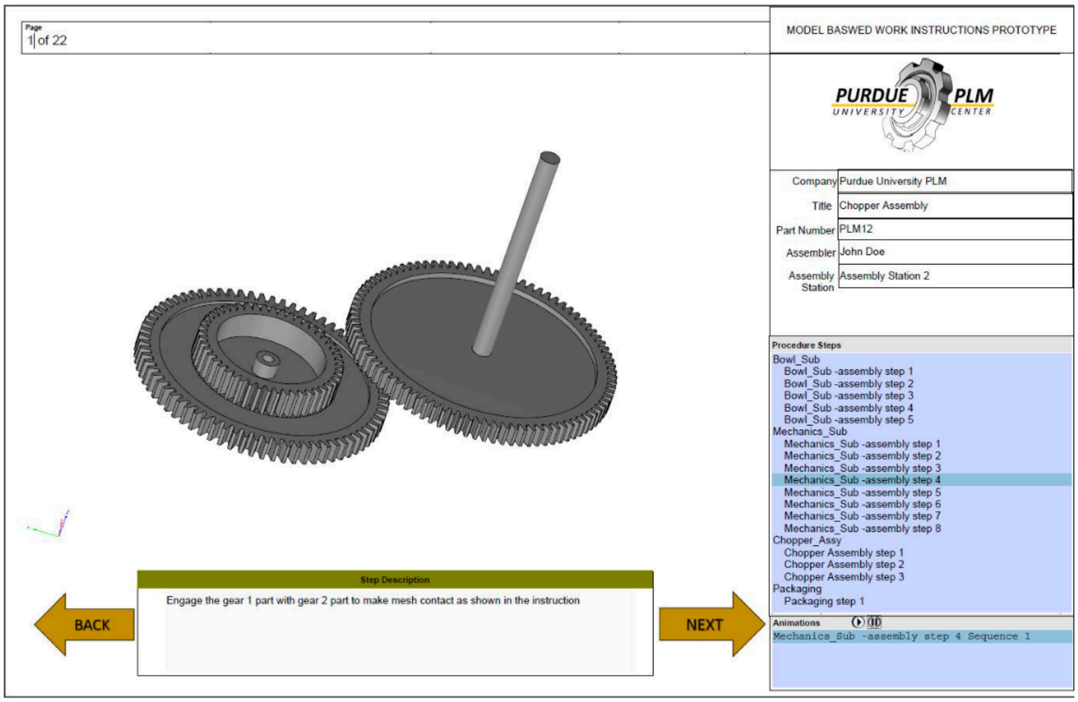

Figure 2. Published Model Based Work Instruction using 3D PDF. (Hartman et al., 2019).

Figure 3. Picture of Paper Work-Instruction

Augmented Reality Work-Instruction in this study adopted the AR system created by the researcher for this study. The application was developed with a combination of software: Unity game engine, Vuforia Augmented Reality SDK, and Blender 3D computer graphics software. The 3D graphics were modeled using Blender's animation toolset and uploaded directly to Unity, where the user interface of the application was designed. Additionally, core AR functionalities such as image target recognition were developed using Vuforia's augmented reality SDK. The AR system was delivered to the participants through the Microsoft Hololens, a popular mixed-reality head-mounted display (HMD). Animations and instructions were presented as holograms that display over the physical parts (fig. 6). The AR work-instruction development in the designer phase and the user phase is shown in figure 4. The application flow of the AR work-instruction is shown in figure 5.

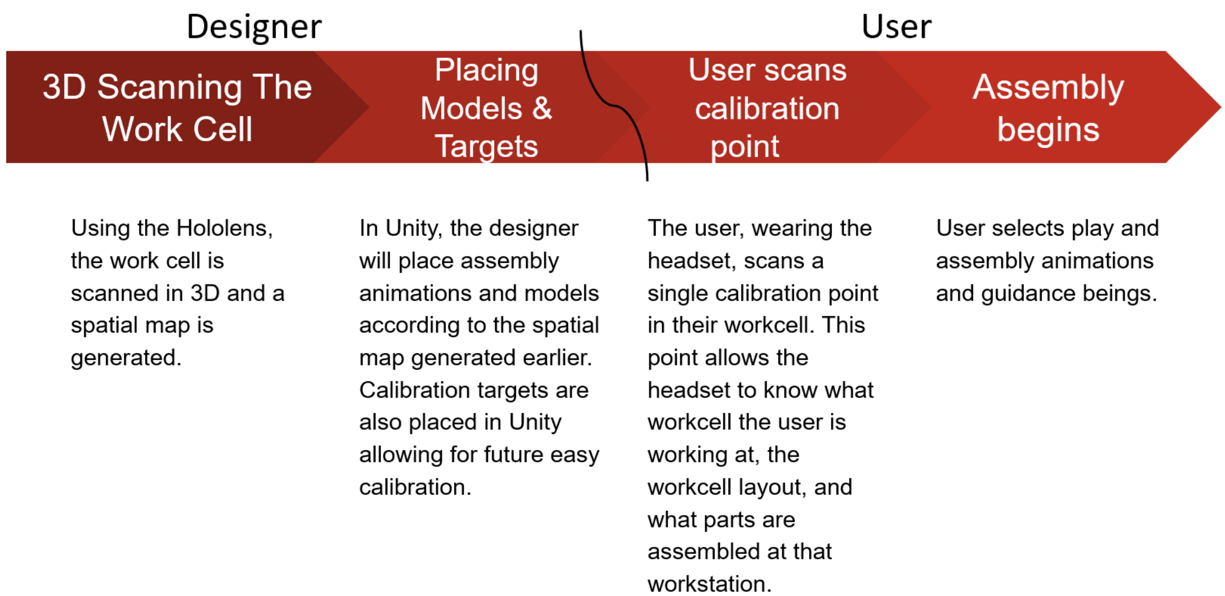

Figure 4. AR Work-Instruction development

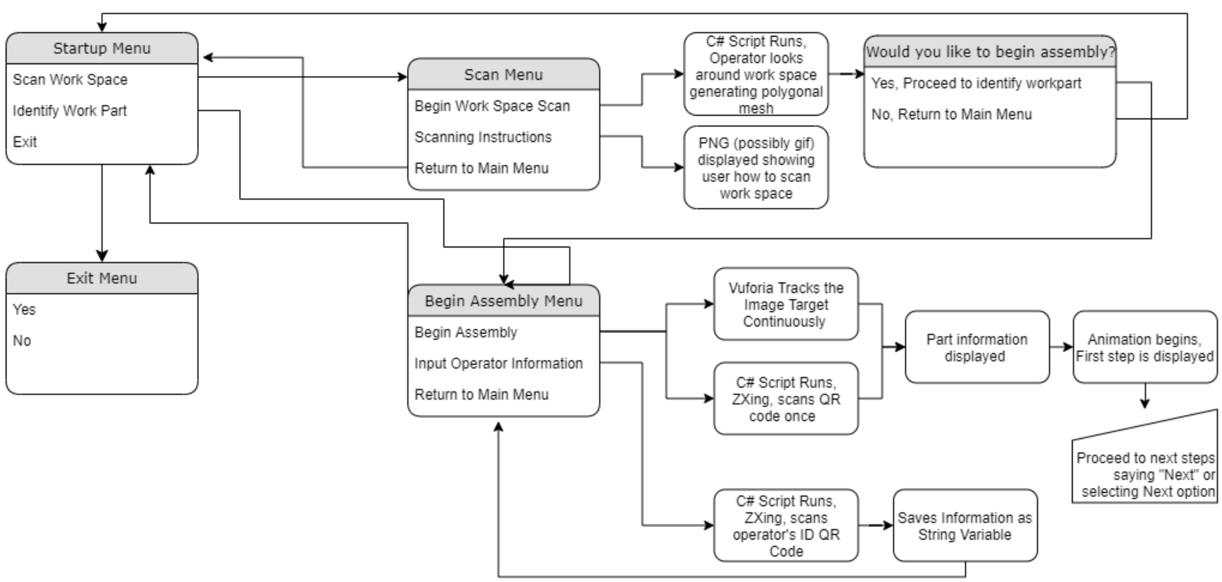

Figure 5. AR Work-Instruction application flow

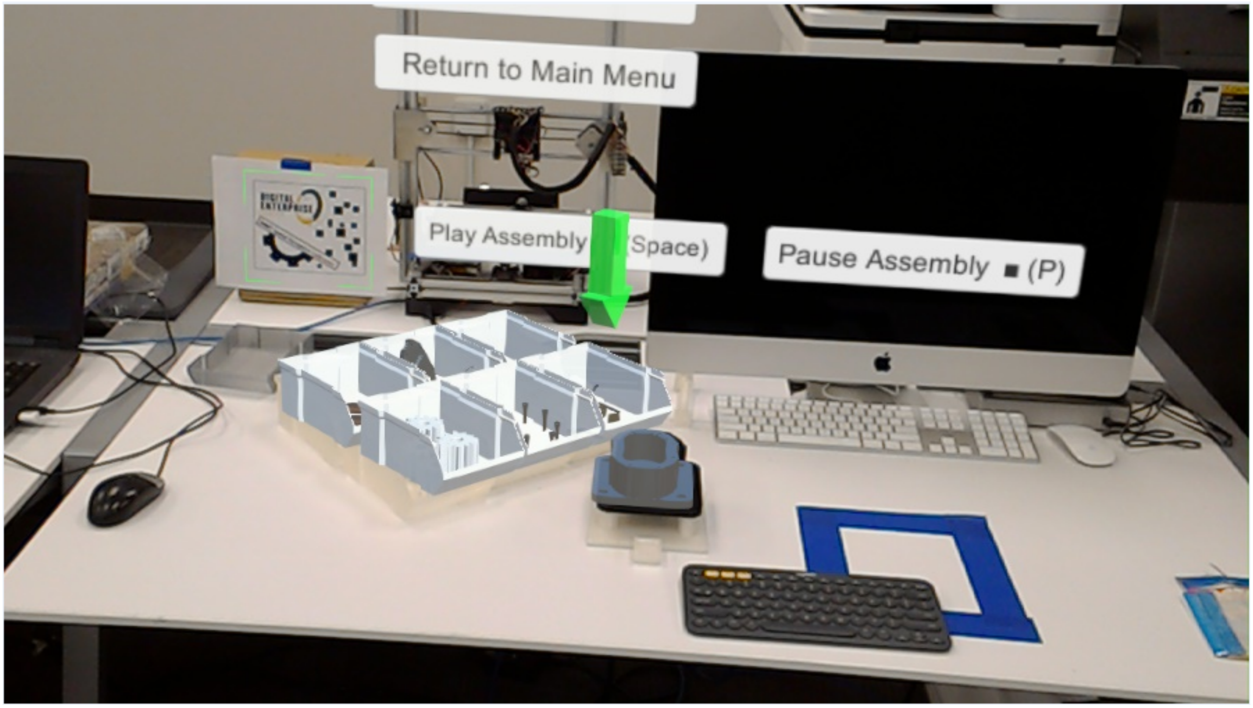

Figure 6. AR Work-Instruction user view

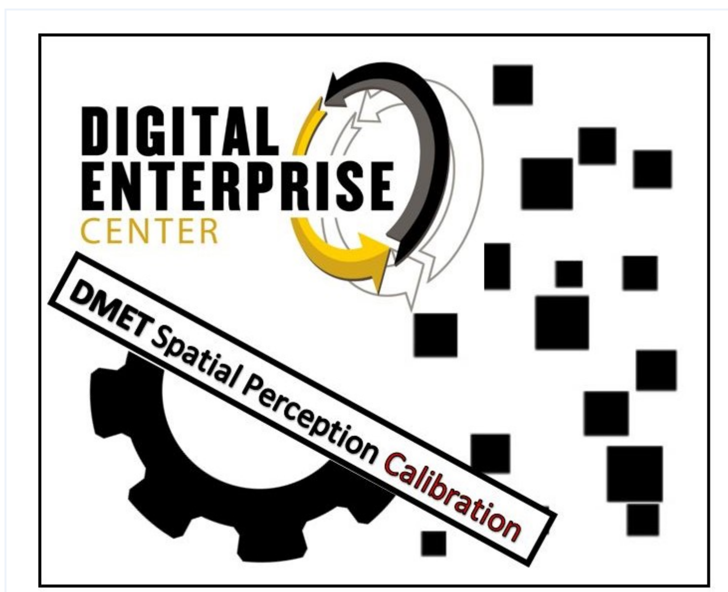

Figure 7. QR code for AR WI Image Target

Research Framework

The experiment followed a between-subjects analysis adopting Büttner et al. (2020)'s methodology, which has similar research objectives as this study. Büttner et al. (2020) compared the knowledge sustainability and training efficiency of three training methods: In-situ personal training, projection-based AR assistive system, and a paper manual. Their study made an initial assumption that the AR assistive training system does not reach the training efficiency of a personal training, and their results confirmed their assumption.

In this experimental design, personal training was not considered as one of the training methods as this study focuses on identifying the effectiveness of the two technology-based interactive training methods.

This research framework challenges Büttner et al. (2020)'s choice of training methods by presenting two digital interactive work instructions as training tools compared to a static work instruction. Moreover, this research design aimed to test Büttner et al. (2020)'s result on knowledge sustainability, and how there are no differences in long-term recall precision between the training methods once an assembly task is properly trained (when a participant masters the assembly by heart).

In order to determine the effectiveness of the interactive WIs as training tools, this study proposed a control group using paper WI, and two experimental groups for AR WI and digital 3D PDF WI. The sample of 30 volunteer-based, Purdue University affiliated participants over the age of 18 who passed the screening were divided into samples of 10. The researcher distributed the participants into each group to minimize variance between the groups, based on the survey result that asks participants' experience on mechanical tools and assembly tasks. The experiment was conducted over three training sessions per each group. Before the first session, participants were asked to complete a survey to collect demographic data as well as their experience level with mechanical tools and assembly tasks.

In the first initial training session, participants were instructed to master the assigned assembly work instructions and try to remember the assembly steps in the correct sequence. The participants were told to complete each assembly cycle from start to finish before starting over again. The participants were also asked to notify the researcher if they believe that they have mastered the assembly task. Data that were collected and documented in the initial training session were the number of training cycles, and the total required training time. Participants in the AR work-instruction group had a 5-minute tutorial session before the initial training session to familiarize with the use of Hololens as well as the general AR environment.

The second training session held place one day after the initial training. This session was to determine the participants' short-term recall of the assembly task as well as to ensure that they master the assembly task in case if any error emerges before the evaluation session. This made sure that all participants reach the same level of training knowledge. The participants were then asked to complete the assembly without any instructions and receive feedback if there were any errors in the end results. If a participant made errors in the finished assembly task, they were instructed to repeat the initial training session. This ensured the end of a training phase, allowing them to move forward to the evaluation session. Data collected in this session were the time it took to complete the task, and the number of errors if any emerged in the first cycle.

The last training session took place one week after the initial training. This session was to evaluate the participants' long-term recall of the trained assembly. Participants were instructed to complete the assembly task without any assistance. The data collected in the evaluation session were the number of errors in the completed assembly. Figure 8 shows an overview of the experiment design.

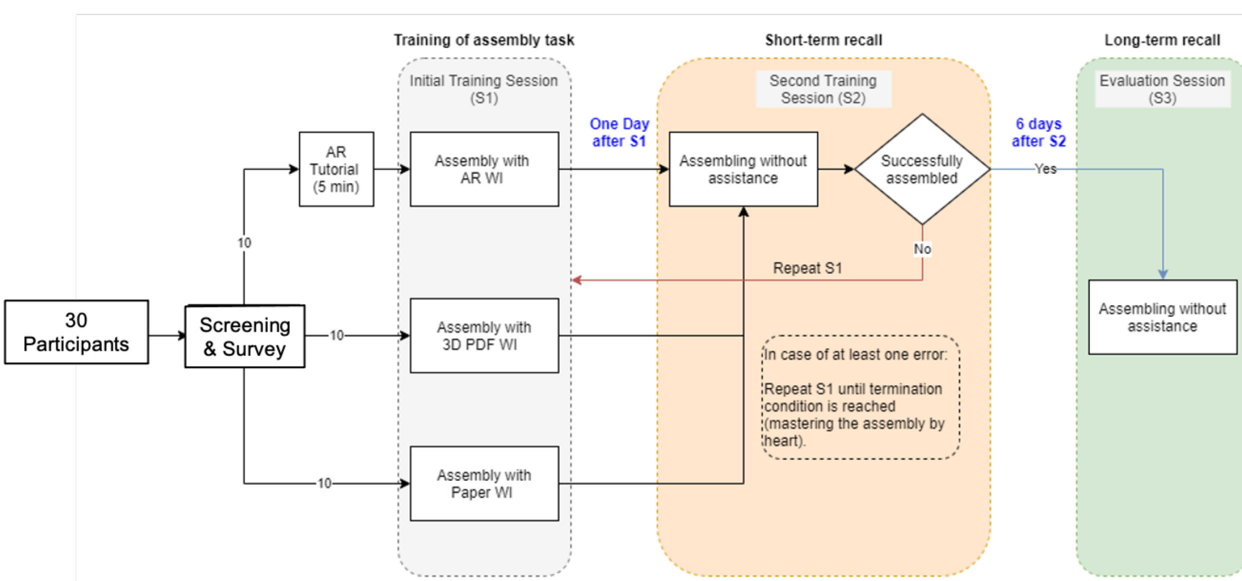

Figure 8. Experiment design adopted from (Büttner et al., 2020).

Training Workspace and Apparatus

The training environment took place at the factory shop floor of the Indiana Manufacturing Institute located in West Lafayette, Indiana. The workbench consisted of a desk, a laptop computer when training with 3D PDF, and a QR-code and a Bluetooth keyboard when training with AR. The QR code for the AR application was used as an image target (fig. 11), allowing the system to detect the correct location for the holograms.

The assembly used throughout the training process was an oil pump model, from an online open-source file sharing website. The assembly model consisted of 21 separate parts, and the work instructions had 10 steps in total. There were two sets of the assembly models ready during each participant's training session to ensure there is no time spent on disassembling the model between assembly cycles. The researcher oversaw replacing the finished assembly with dis-assembled parts after each cycle (fig. 9).

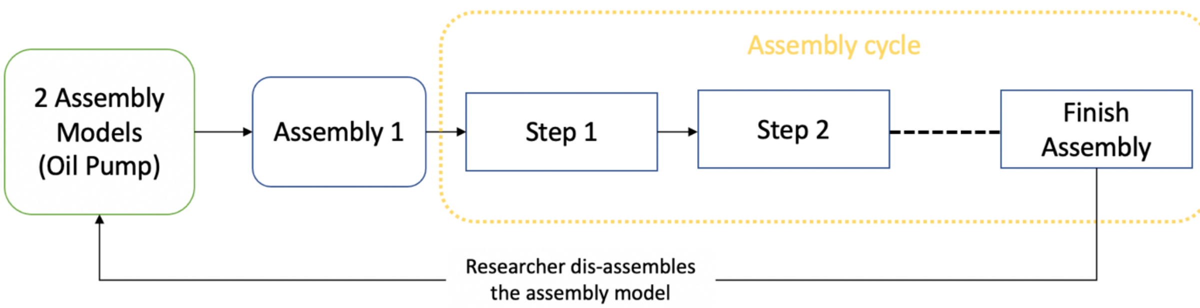

Figure 9. Assembly cycle flow

Microsoft Hololens was used as the HMD for AR work-instruction. This choice was made because it provides stable tracking at low latencies (Blattgerste et al., 2018). Moreover, Hololens allows "spatial tracking" which is a critical functionality on registering the holograms on the physical assembly environment. A Bluetooth keyboard was used with the AR application for users to move forward within the assembly steps, and restart when a cycle is over.

Survey

On the day of the initial training session, participants were required to complete an online survey before starting the initial training for collection of demographic data as well as the participant's experience with mechanical tools, experience with assembly, and their field of work experience. Google Forms was used to create the online survey. The demographic data collected each participant's name, email address, age to ensure that they are above the age of 18, and their current grade-level if they identified as a student and occupation if they did not identify as a student. To evaluate mechanical experience, the question was presented in a Likert scale of 1 to 5, 1 being 'No experience with mechanical tools', and 5 being 'Mechanically inclined'. The assembly experience was also evaluated on a Likert scale of 1 to 5, 1 being 'No experience', and 5 being 'confident in assembling'. The field of work experience was presented in a multiple-choice question, and the options were: Factory, office, retail, or 'No work experience'.

Data Analysis

Throughout the experiment, one-way analysis of variance (ANOVA) was used to compare the number of training cycles, training time, and number of errors between the three independent groups. The one-way ANOVA is "used to determine whether there are any statistically significant differences between the means of two or more independent groups" (Laerd Statistics, 2014). However, there are limitations with one-way ANOVA tests as it does not show which specific groups were statistically different from each other. Since this study design has three groups, a post hoc test was conducted to determine which of the groups differ from each other (Laerd Statistics, 2014).

Number of Training Cycles

A one-way ANOVA test was conducted to see the significance between the three conditions in the first and second training sessions. If the differences between the three conditions were shown as significant, a post hoc test was conducted to evaluate the significant differences between two conditions.

Training Time

The mean values of the training times in sessions 1 and 2 were measured to seek out any significant difference between the conditions. Moreover, a one-way ANOVA test was done to analyze the differences between the 3 conditions, as well as a post hoc test to seek the difference between two conditions if the one-way ANOVA resulted a significant difference.

Performance after One Day (Session 2)

To measure the performance of the participants after the second session, means of errors between the training conditions that occurred on the second training session were measured and compared. The variables measured in this section were number of errors occurring during the first assembly cycle in training session 2. Following the statistic tests mentioned above, a one-way ANOVA test was done to analyze if there is a significant difference between the three conditions and an additional post hoc test to distinguish the significance between two conditions.

Performance after One Week (Evaluation Session)

Following the statistic tests mentioned in the previous sections, the number of errors that occurred during the assembly cycle without assistance was measured. A one-way ANOVA test was conducted and if necessary, an additional post hoc was further conducted. Variables measured in this session are the number of all errors during the first assembly cycle in the evaluation session.

Summary

This chapter provided an overview of the experiment design that will be used to collect relevant data to answer the research question as well as the sub-questions. The proposed experiment process was conducted over a week period, where two training sessions and one evaluation session took place.

RESULTS

This chapter presents the results that were gathered during the data collection portion of the study. It will first present the participant data that were gathered in the demographics survey. This chapter will then present the analyzed data on the required training cycles that occurred in sessions 1 and 2, required training times in sessions 1 and 2, and the number of errors that occurred in session.

Demographics

A total of thirty participants went through the research experiment. Each experimental group (AR, 3D PDF) and control group (Paper) consisted of ten participants. Demographic data was collected through the survey that was held on the first day of data collection, before starting the initial training session. The first experimental group that tested with the AR WI consisted of 3 undergraduate students, 5 PhD students, 1 master's student and 1 industry professional. The second experimental group that tested with the 3D PDF WI consisted of 3 undergraduate students, 5 PhD students, 1 master's student and 1 industry professional. The control group that tested with the paper WI had 3 undergraduate students, 3 PhD students, 3 master's students and 1 industry professional (fig. 10).

The recruited participants in this study relate with those in a previous research done by Buttner and colleagues (2020), where 22 of the participants were students from two courses at the authors' university and 11 were from the university community including interns, employees, and students from other faculties. Similarly, this research study recruited Purdue University community members, but the scope was narrowed down to Purdue students and employees at the IMI which is a Purdue University research institute. They represent the current and upcoming work force in the manufacturing, engineering and technology industry which is relevant to the study experiment.

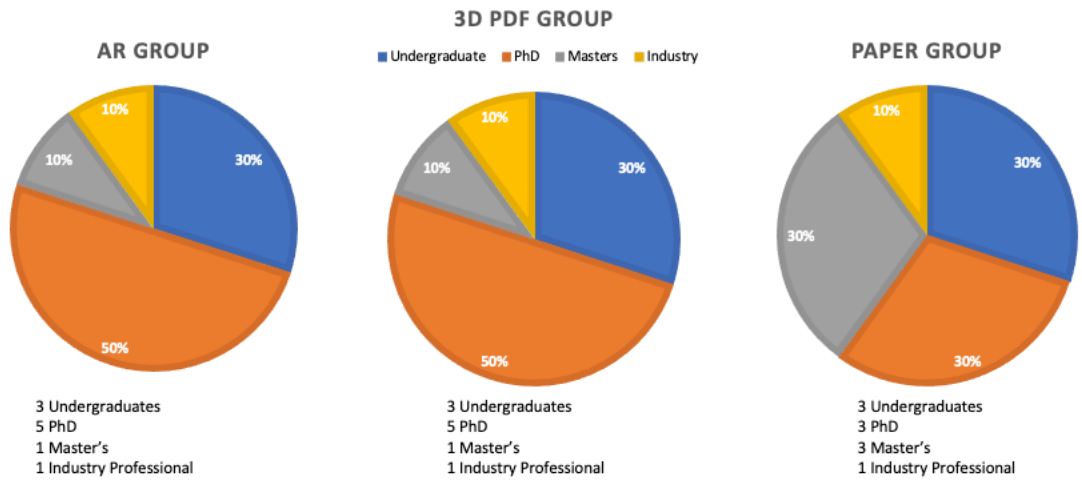

Figure 10. Pie Chart of Participant Demographics

Background and Experience

All undergraduate and graduate students who participated in the study were enrolled in either Purdue University's college of engineering or polytechnic institute. The three industry professionals were staffs working at the Indiana Manufacturing Institute. The survey polled participants' experience in different work settings and multiple answers were permitted. As shown in figure 11, the results indicated that the participants had the most work experience in an office setting (28 answers) followed by factory setting (14 answers) and retail setting (11 answers).

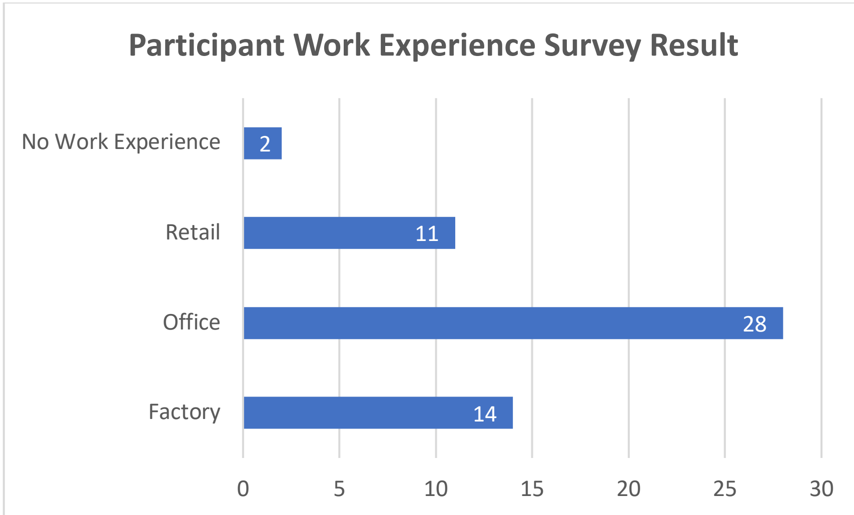

Figure 11. Bar Graph of Participant Work Experience Survey Result

The survey also polled the participants' experience with mechanical tools and assembly tasks. The question asking their experience with mechanical tools was presented in a Likert scale from 1 to 5, 1 indicating having no experience with mechanical tools and 5 being mechanically inclined. The question asking their experience with assembly tasks such as IKEA's furniture assembly was also presented in a Likert scale of 1 to 5, 1 indicating having no experience in assembly tasks and 5 being confident in assembling.

From survey results as shown in figure 12, all groups had similar experience levels on mechanical tools, but the paper group had a slightly higher experience level on assembly tasks. The AR WI group had an average of 3.5 on their experience in mechanical tools, and 3.8 on their experience in assembly tasks. The 3D PDF group had an average of 3.8 on their experience with mechanical tools, and 3.8 on their experience in assembly tasks. The paper group had an average of 3.7 on their experience with mechanical tools and had 4.1 on their experience in assembly tasks.

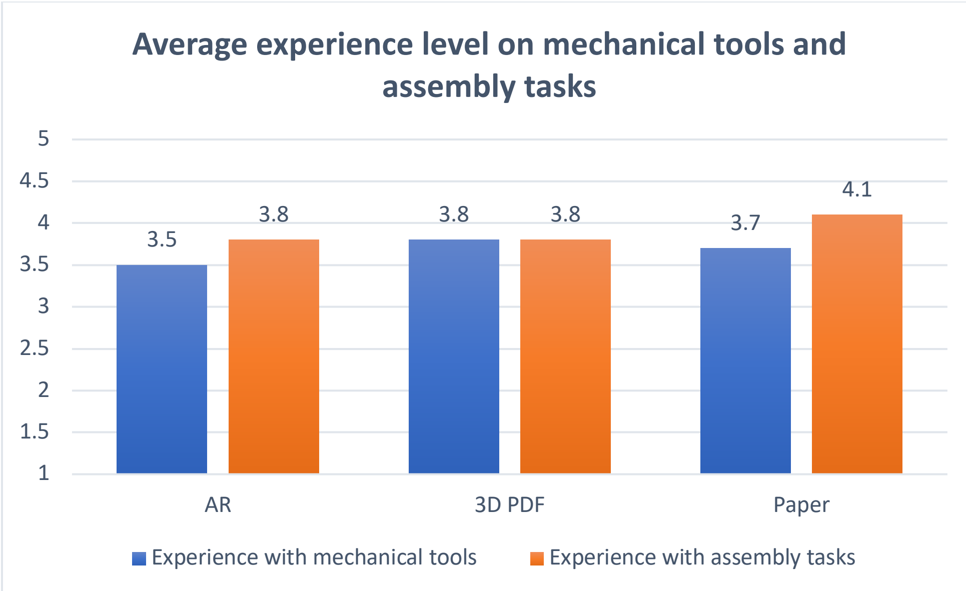

Figure 12. Bar Graph of Participants' Average Experience Level on Mechanical Tools and Assembly Tasks.

Results

In this section, the collected data from the experiment are analyzed and presented in forms of charts, graphs and tables. The variables collected will be grouped to present the number of training cycles, training time in sessions 1 and 2, performance after one day and performance after one week.

Number of Training Cycles

A comparison was made between the number of training cycles in training sessions 1 and 2 of the three groups (fig. 13). In the first training session, participants in the AR group required an average of 1.6 cycles (SD = 0.52), followed by participants in the 3D PDF group with an average of 2.1 cycles (SD = 0.57) and participants in the paper group with an average of 2.2 cycles (SD = 0.63).

A one-way ANOVA test was computed to see if there were any significant differences between the three groups in terms of number of training cycles in session 1 (table 2). The following assumptions were made to conduct the ANOVA test: All populations have equal variance, and the populations are normally distributed. It is observed that the results between the groups are statistically similar. The resulting p-value of 0.0597 is slightly greater than the 95%

confidence level, leading to a conclusion that this test did not result in statistically significant data.

Table 2. ANOVA for number of training cycles in session 1.

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.06666667	2	1.03333333	3.13483146	0.05967019	3.35413083
Within Groups	8.9	27	0.32962963			
Total	10.9666667	29				

On the second training session that took place one day after the first session, participants in the 3D PDF group required the least amount of training cycles averaging at 0.50 cycles (*SD* = 0.53). Five out of ten participants who trained with the 3D PDF WI did not make any errors and therefore did not have to do further training. Participants in the paper group required an average of 1.00 training cycles (*SD* = 0.82), having three participants with no errors. The participants in the AR group required the most amount of training cycles averaging at 1.10 cycles (*SD* = 0.99) and had four participants who made no errors.

To further analyze the result, a one-way ANOVA test was conducted (Table 3) to see if there are significant differences between the three groups regarding the required number of training cycles in session 2.

Table 3. ANOVA for number of training cycles in session 2.

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.06666667	2	1.03333333	1.60344828	0.21977503	3.35413083
Within Groups	17.4	27	0.64444444			
Total	19.4666667	29				

The ANOVA result indicated that the three groups are statistically similar when it comes to the number of training cycles required in session 2. The resulting p-value of 0.2198 is greater than the 95% confidence level, leading to the conclusion that this test did not result in statistically significant difference between the groups.

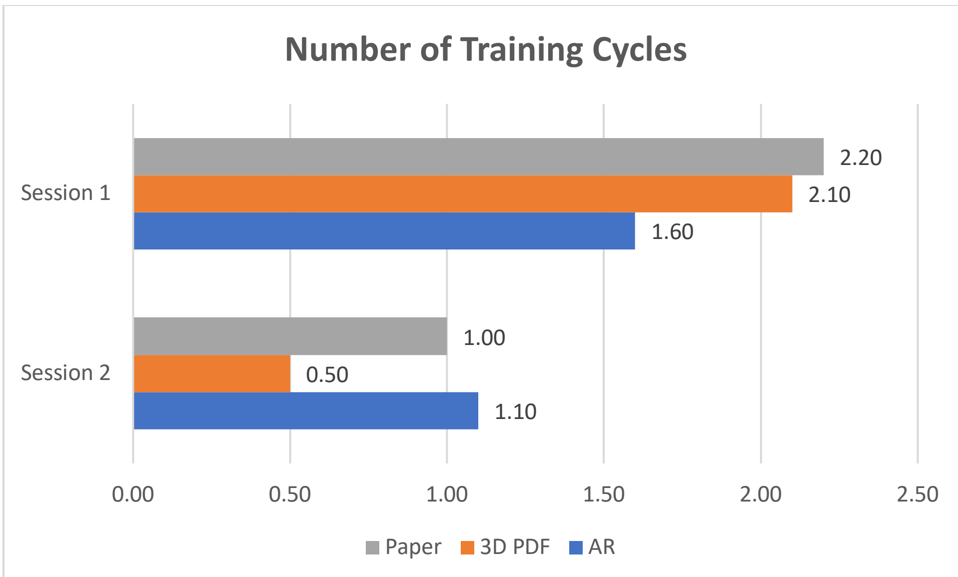

Figure 13. Bar graph of number of training cycles for the two training sessions.

Training Time

In this section, a comparison is made on the required training times for each group for training sessions 1 and 2 (fig. 14). In training session 1, participants in the 3D PDF group required least amount of time, averaging at 441.3 seconds (7.36 mins., *SD* = 169.88 sec). Participants in the paper group follows next, averaging at 564.5 seconds (9.41 mins., *SD* = 194.39 sec). Participants in the AR group required the most training time, averaging at 659.9 seconds (11.00 mins., *SD* = 283.33 sec).

A one-way ANOVA test was conducted to see if there is any significant difference between the three groups regarding the required training time in session 1. The result (Table 4) indicated that the test did not yield statistically significant data. The p-value of 0.1050 is greater than the 95% confidence level, providing a conclusion that the three means are not statistically different from each other.

Table 4. ANOVA for required training time in seconds for session 1.

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	240217.867	2	120108.933	2.45243079	0.1050372	3.35413083
Within Groups	1322337.5	27	48975.463			
Total	1562555.37	29				

The result in the second training session follows a similar pattern. Participants in the 3D PDF group required the least amount of time, with an average of 56.00 seconds (0.93 mins., *SD* = 60.56 sec). As mentioned in the previous section, 50% of the participants in this group did not make any errors therefore did not continue with additional training. Participants in the paper group required an average of 114.7 seconds (1.91 mins., *SD* = 88.46 sec) and participants in the AR group required an average of 188.6 seconds (3.14 mins., *SD* = 165.41 sec). Unlike the result of the first session, the ANOVA test result (Table 5) shows a clear difference in the three groups for session 2.

Table 5. ANOVA for required training time in seconds for session 2.

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	88298.8667	2	44149.4333	3.40896429	0.04785489	3.35413083
Within Groups	349676.5	27	12950.9815			
Total	437975.367	29				

The resulting p-value of 0.0479 is below the 95% confidence level, indicating that there is a statistically significant difference between the three groups regarding training time for session 2. To further analyze the data, a Scheffe test was conducted to compare training time results. The post hoc Scheffe test provides a comparison of various group means, by analyzing each coupling of the group data to assess any statistical differences (Allen, 2017). This test was run on SPSS and the results are shown in table 6.

Table 6. Scheffe test for training time in seconds for session 2.

Multiple Comparisons

Dependent Variable: S2 Training time (s)

Scheffe

(I) WI Type	(J) WI Type	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
3D PDF	AR	-132.60*	50.894	.048	-264.42	-.78
	Paper	-58.70	50.894	.522	-190.52	73.12
AR	3D PDF	132.60*	50.894	.048	.78	264.42
	Paper	73.90	50.894	.362	-57.92	205.72
Paper	3D PDF	58.70	50.894	.522	-73.12	190.52
	AR	-73.90	50.894	.362	-205.72	57.92

*. The mean difference is significant at the .05 level.

Homogeneous Subsets

S2 Training time (s)

Scheffe[a,b]

WI Type	N	Subset 1	Subset 2
3D PDF	10	56.00	
Paper	10	114.70	114.70
AR	10		188.60
Sig.		.522	.362

a. Uses Harmonic Mean Sample Size = 10.000.
b. Alpha = .05.

The Scheffe test revealed that the 3D PDF group is statistically different from the AR group ($p = .048$), but no difference was detected between the AR group and the paper group ($p = .362$) or between the 3D PDF group and the paper group ($p = .522$).

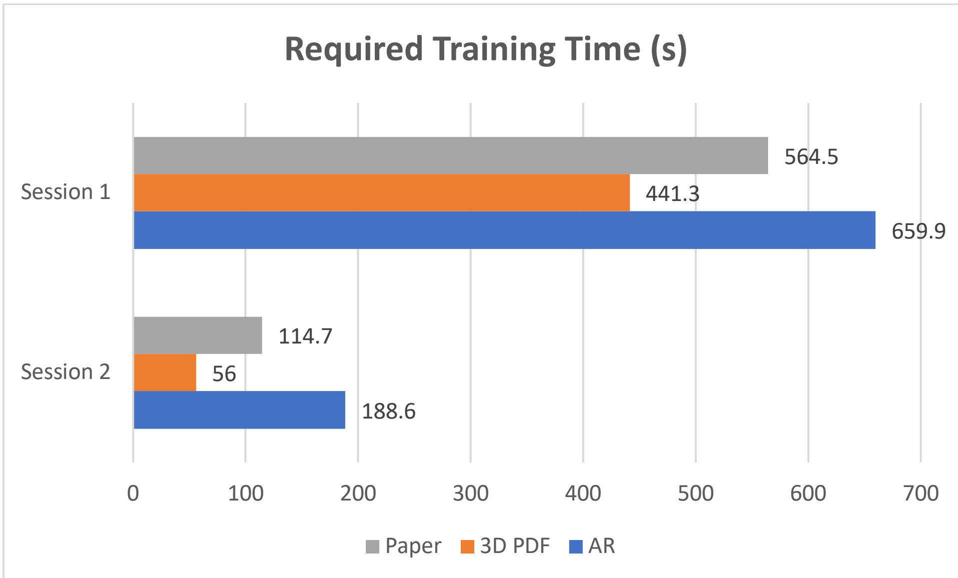

Figure 14. Bar graph of required training times in seconds for the two training sessions.

Performance after One Day

The number of errors after 24 hours of the three groups was collected and analyzed. Participants in the AR group had the least number of errors with an average of 0.80 ($SD = 0.79$) followed by the 3D PDF group averaging at 0.90 ($SD = 1.10$) and the paper group having an average of 1.20 ($SD = 1.03$).

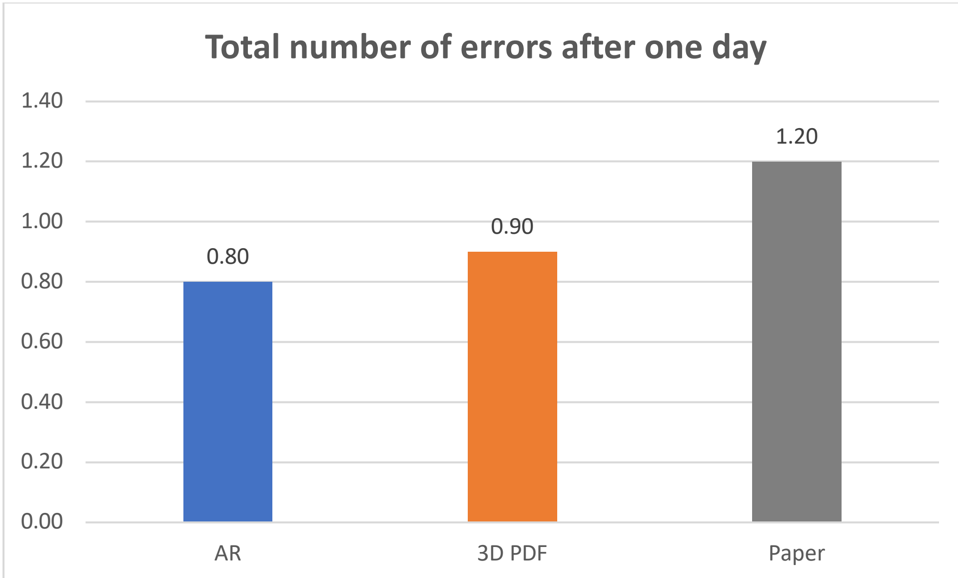

Figure 15. Bar graph of total number of errors occurred after one day (session 2).

To further analyze the data, a one-way ANOVA test was conducted to see if there are any significant differences between the three conditions. The resulting p-value of 0.6434 was greater than the 95% confidence level, indicating that there is no significant difference between the means of the three groups for the number of errors occurred during session 2.

Table 7. ANOVA for the total number or errors occurred after one day (session 2).

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.86666667	2	0.43333333	0.44827586	0.64339658	3.35413083
Within Groups	26.1	27	0.96666667			
Total	26.9666667	29				

Performance after One Week

The data for total number of errors that occurred after one week during the evaluation session was collected and analyzed. Like the previous results, the AR group yielded the least number of errors with an average of 0.20 (*SD* = 0.42), followed by the 3D PDF group averaging at 0.9 (*SD* = 0.99) and the paper group having the greatest average of 1.10 (*SD* = 0.88).

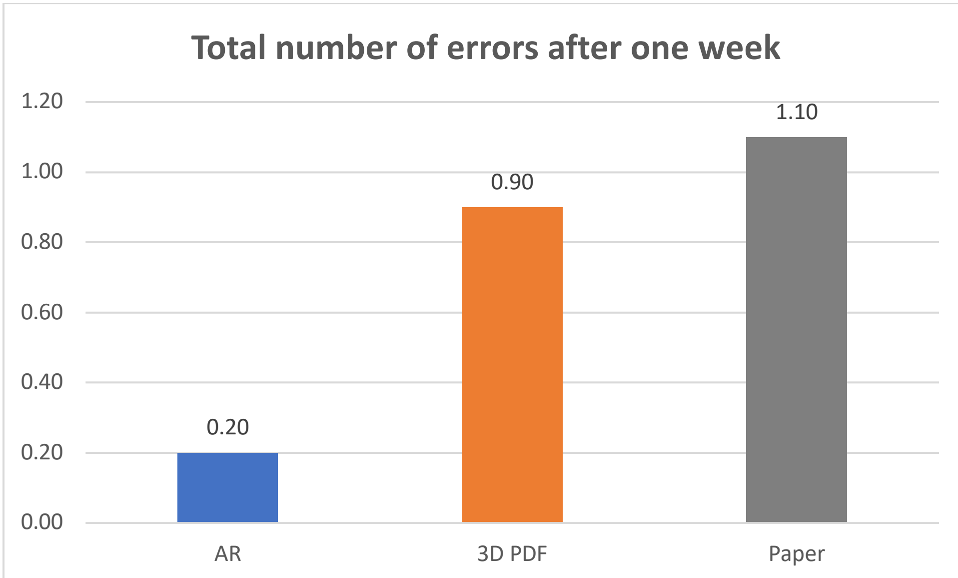

Figure 16. Bar graph of total number of errors occurred after one week (evaluation session).

Table 8. ANOVA for the total number of errors occurred after one week (evaluation session).

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4.46666667	2	2.23333333	3.46551724	0.04574567	3.35413083
Within Groups	17.4	27	0.64444444			
Total	21.8666667	29				

The result of the ANOVA test showed that the p-value is 0.0457 which is lower than the 95% confidence level. It can be concluded that there is at least one statistically significant difference between the means of the three conditions. A post hoc comparison was made using the Scheffe test to seek out the significant differences.

Table 9. Scheffe test for total number of errors that occurred after one week (evaluation session).

Multiple Comparisons

Dependent Variable: All errors after one week

Scheffe

(I) WI Type	(J) WI Type	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
3D PDF	AR	.70	.386	.212	-.30	1.70
	Paper	-.30	.386	.742	-1.30	.70
AR	3D PDF	-.70	.386	.212	-1.70	.30
	Paper	-1.00*	.386	.050	-2.00	.00
Paper	3D PDF	.30	.386	.742	-.70	1.30
	AR	1.00*	.386	.050	.00	2.00

Based on observed means.

*. The mean difference is significant at the .05 level.

All errors after one week

Scheffe[a,b]

WI Type	N	Subset 1	Subset 2
AR	10	.20	
3D PDF	10	.90	.90
Paper	10		1.20
Sig.		.212	.742

Means for groups in homogeneous subsets are displayed.

Based on observed means.

a. Uses Harmonic Mean Sample Size = 10.000.

b. Alpha = .05.

The result of the Scheffe test revealed that there is a significant difference between the AR group and the paper group with a p-value of 0.050 which is equal to the 95% confidence level. However, no significant differences were detected between the AR group and the 3D PDF group (p = .212) or between the 3D PDF group and the paper group (p = .742). It can be concluded that the AR group performed significantly better than the paper group.

Chapter Summary

In this chapter, the results of the study experiment were presented using charts and graphs, and an analysis was provided for the collected data using statistical tests. 30 participants participated in this study, with 10 participants in the experimental groups each using AR WI and 3D PDF WI, and the control group using the paper WI. The mean comparisons between the three groups for each sub-chapter were done using the one-way ANOVA test and an additional post hoc Scheffe test if the ANOVA test had shown significant results. The number of training cycles that occurred during sessions 1 and 2 showed no significant differences between the three conditions. There were also no significant differences between the three groups for the required training time in the initial session. However, there was a significant difference between the 3D PDF group and the AR group for the required training time in session 2 illustrating that the users of the 3D PDF WI needed significantly less time for training compared to the users of AR WI in the second training session. Comparing the number of errors that occurred after one day (session 2), the results showed that the means of the three groups are statistically similar. However, the results of the evaluation session that occurred one week after the initial training session indicated that there is a significant difference between the three conditions, and the Scheffe test revealed that there is a significant difference between the means of the AR group and the paper group. It was concluded that the AR group had significantly less errors after one week compared to the paper group.

DISCUSSION

This chapter will discuss the findings from the results according to the proposed hypotheses about training efficiency and knowledge sustainability. Furthermore, it will provide research limitations as well as future research suggestions.

Training Efficiency

To measure training efficiency for the different types of work-instructions used in this study, the number of training cycles that occurred during the initial session and the second training session, and the required training time for each session were taken into consideration. The results showed that there was no significant difference between the groups during the first two sessions of the study, indicating that the three types of work instructions had similar effects on the number of training cycles the participants required. Regarding the required training time, the ANOVA test did not show any significant difference between the three conditions in the initial training sessions. It can be interpreted that all participants took about the same amount of time during initial training regardless of the assigned type of work instructions. However, when looking into the training time results of session 2, it was discovered that the 3D PDF group took significantly less time compared to the AR group. This is an interesting finding especially because the only significant difference found among the three groups was between the two experimental groups even though the required training cycles were about the same. One explanation for this would be the limited field of view of the Hololens 1. While both the 3D PDF WI and the AR WI provided guided animations per step, the AR WI users had to physically walk back from the work station for each step to get a wider view of the holographic animations that are overlaid on the physical assembly parts. Further explanation of the Hololens' limited field of view is discussed in the 'Limitations' section of this chapter.

Regarding the total number of errors that occurred during the second training session, results revealed that there is no statistically significant difference between the three groups. Even if the 3D PDF group yielded the fastest training time in the second training session, it does not support the researcher's assumption that the 3D PDF is learned the fastest because the error results do not show any evidence. Therefore, H1, H2 and H3 are not supported by the study experiment.

Knowledge Sustainability

Regarding the data of the total number of errors one week after the initial training session, the results showed that there is a significant difference between the three groups. The statistical tests revealed that there is a significant difference between the AR group and the paper group. Even if the participant performance after one day did not have significant results, the participant performance after one week indicated that the information obtained through the AR WI yielded greater memorability compared to that of paper WI. The participants in the AR group were able to remember much better and successfully reproduce the oil pump assembly task with significantly fewer errors than those in the paper group, which supports the researcher's assumption that spatially displayed information such as the AR WI is better remembered than static information displayed on a paper WI.

While it is observed that there is no difference between the training methods regarding the participants' learning speed, it is proven that the AR WI successfully prevents mislearning of content and keeps the obtained knowledge better compared to the paper WI. An interesting outcome for the 3D PDF WI is that it does not have a significant advantage compared with the paper WI when it comes to remembering the assembly process. Therefore, H4 and H6 are rejected but H5 is supported by the experiment.

Table 10. Accepted and rejected hypotheses in this study.

H1	Assembly tasks are learned faster with a digital 3D PDF instruction than with a paper work instruction.	Reject
H2	Assembly tasks are learned faster with an AR work instruction than with a paper work instruction.	Reject
H3	Assembly tasks are learned faster with an AR work instruction than with a digital 3D PDF work instruction.	Reject
H4	An assembly task trained through a digital 3D PDF work instruction is better remembered than one trained by a paper work instruction.	Reject
H5	An assembly task trained through an AR work instruction is better remembered than one trained by a paper work instruction.	Accept
H6	An assembly task is remembered equally well, regardless if it is trained through an AR work instruction or through a digital 3D PDF work instruction.	Reject

Limitations

The first limitation this study faced was the limited field of view of the Hololens when training with the AR WI. As mentioned in the previous section, participants in the AR group took the longest time to complete training in the first two sessions even though the number of training cycles did not result in a significant difference between the three training methods. This is mainly because the participants training with the AR WI had a small field of view when using the head-mounted display. The Microsoft Hololens 1 provides a field of view of approximately 34° which is significantly less than the average human eye field of view of 120° (Nishino & Nayar, 2006). This has hindered the participants' ability to stand in one position while following the guided assembly animations. Participants in the AR group often had to step back from the work station after progressing each step to see a wider view of the assembly animation, resulting longer time to complete each cycle compared with the participants in the 3D PDF and paper group.

The second limitation for this study was the level of experience of the participants. The survey result revealed that the participants generally had a high level of experience with mechanical tools and assembly tasks which might have affected the low number of required training cycles (≤3 cycles). This unforeseen variable could have been the reason why there was no significant findings regarding the training efficiency of the training methods.

Future Recommendations

Based on the limitations discussed above, this study would be more effective if the AR WI utilized an HMD that provides a larger field of view than the Hololens 1. This will eliminate the need for participants to take excessive time on following the animation guided instruction by physically moving back and forth from the work station. If it had been implemented in a real factory environment, the assigned work space of the users might not be large enough for them to move around and the required time for training would not be considered efficient.

Another recommendation for the AR WI would be implementing a responsive system that detects the user's progress within the assembly process. The AR program that was used in this study is not able to determine if the user is following the instruction correctly. By implementing artificial intelligence (AI) technology into the program, it could scan the physical parts that the users are assembling and only let them move on to the next step if the current step had been performed with no errors.

While this study focuses on the training efficiency and the knowledge sustainability of the interactive training methods, it does not investigate the cost of implementing the required training tools. From an industry standpoint, cost is an important factor for companies when building successful training programs. While this study proved that training with the AR WI yields greater knowledge sustainability compared to training with a paper WI, further investigation should be conducted to see the investment to implement novel technology-assisted training systems would generate a tangible return.

Moreover, the variables in this study could be manipulated in future studies to yield dynamic results. For instance, the timeline of the study could be prolonged beyond seven days to see how the participants' knowledge retention rate changes overtime for each training group. It would also be insightful to investigate the relationship between knowledge retention and repetition of training. Shail (2019) claimed that the retention rate is improved by repeating a task multiple times over a period of time, and Jeske et al. (2014) argued that the more a person repeats the assembly tasks, the more irrelevant the instructional method becomes. If the participants were given multiple training sessions and evaluation sessions, it could reveal valuable data to see if the three instructional methods have a difference in knowledge sustainability after multiple training sessions over a longer timeline.

Another variable that can be manipulated would be the number of participants in the study. While this study experimented with 30 subjects, recruiting more participants could result further findings regarding training efficiency and knowledge sustainability as it would provide a larger set of data points to analyze. Moreover, the study could take a different approach on the participant demographics. For instance, experimenting with employed workers in the manufacturing industry who have many years of assembly experience could give accurate insight into the effectiveness of the different training tools if they were implemented in industry settings.

Conclusion Statement

In this research study, the primary goal was to determine if interactive work instructions such as the augmented reality work instructions and 3D PDF work instructions have an advantage on training efficiency and knowledge sustainability compared to the static paper work instructions. The results of this study showed that there are no differences between the three training methods when it comes to training efficiency, but AR WI has proved to be more effective in sustaining the user’s long-term recall precision than the paper WI. As a result, H5 (An assembly task trained through an AR WI is better remembered than one trained by a paper WI) was supported by the findings of this study. With no prior research conducted on comparing two technology-based interactive work instructions (HMD-based AR WI and 3D PDF WI) with a static paper work instruction, the data presented through this study aims to provide knowledge to support future research in effective assembly training methods.

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APPENDIX A SURVEY

Survey for Research Experiment

Thesis: The Effect of Manufacturing Work Instructions as a training tool for assembly tasks
Researcher: Soho Yun (Master's student in CGT)

This is a pre-survey for participants in this thesis study. Participants will be required to submit this form prior to their initial training session.

* Required

1. Please enter your name *

   ____

2. Please enter your email address *

   ____

3. Please enter your age *

   ____

4. Please indicate your current grade level (If none applies, select 'Other'). *

   Mark only one oval.

   - ( ) Master's Program
   - ( ) PhD Program
   - ( ) Undergraduate Program
   - ( ) Other: ______________________________

5. What college are you enrolled in? (If none applies, select 'N/A') *

Mark only one oval.

- ( ) College of Engineering
- ( ) Polytechnic Institute
- ( ) Other
- ( ) N/A
- ( ) Other: ____________________

6. How experienced are you with mechanical tools? *

Mark only one oval.

	1	2	3	4	5	
No experience	( )	( )	( )	( )	( )	Mechanically Inclined

7. How experienced are you with assembly work (i.e. IKEA furniture assembly)? *

Mark only one oval.

	1	2	3	4	5	
No experience	( )	( )	( )	( )	( )	Confident in assembling

8. Please indicate if you have work experience in any of these work settings: *

Check all that apply.

- [ ] Factory
- [ ] Office
- [ ] Retail
- [ ] No work experience

Other: [ ] ____________________

APPENDIX B FORMS

RESEARCH PARTICIPANT CONSENT FORM
The Effect of Interactive Manufacturing Work Instructions as a training tool for Assembly Tasks
Dr. Nathan Hartman
Computer Graphics Technology
Purdue University

Key Information
Please take time to review this information carefully. This is a research study. Your participation in this study is voluntary which means that you may choose not to participate at any time without penalty or loss of benefits to which you are otherwise entitled. You may ask questions to the researchers about the study whenever you would like. If you decide to take part in the study, you will be asked to sign this form, be sure you understand what you will do and any possible risks or benefits.

What is the purpose of this study?

This protocol is part of a research study being conducted by Soho Yun (graduate researcher) and funded by the Digital Enterprise Center (DEC) at Purdue University. This research study will compare interactive digital work instructions (WI) to traditional static work instructions, typically found in 2D electronic or paper form. The study aims to investigate how effective Augmented Reality (AR) WI and digital 3D PDF WI are in terms of training efficiency and long-term knowledge retention of the users compared to training with a paper WI. As part of this research, participants who are Purdue University students in College of Engineering and the Polytechnic Institute will be asked to train themselves on an assembly task using the assigned method of work instructions. The training method is assigned based on the participant's pre-survey results. The research study will be conducted over three sessions per participant over the course of one week. The expected enrollment is up to 50 participants.

What will I do if I choose to be in this study?

If you agree to participate in the study, you will be asked to engage in three 30-minute sessions. All three sessions will take place in a factory shop floor setting with the graduate researcher on site. In the first session (S1), you will be asked to train yourself to assemble a component using the assigned training method. The three training methods are: AR WI, digital 3D PDF WI and paper WI. You will be following along the WI and repeating the assembly cycle until you feel that you have mastered the assembly process by heart. The second training session (S2) will take place 24 hours after S1. You will be asked to assemble the component without any guidance and if there is at least one error, you will be asked to repeat S1 until you feel that you have mastered the assembly steps. The last session (S3) will take place one week after S1 where you will be asked to assemble the component once. The researcher will record the training time and the number of cycles it took for you to complete training during S1 and S2. Moreover, your assembly performance in S2 and S3 will be recorded. Participants assigned with AR WI will go through a 5-minute tutorial before starting S1 where they can familiarize themselves with using the AR head-mounted display (HMD). All three sessions will be audio and video recorded and inspected for data analysis.

How long will I be in the study?

The total time commitment is limited to three 30-minute sessions over one week.

What are the possible risks or discomforts?

The risk level for this study is minimal and is less than what the participant would encounter in daily assembly related tasks. Each session will be audio and video recorded. This audio and video recording will only be used by the researcher to accurately record the training time, number of cycles completed, and participant assembly performance without guidance. Once anonymized and analyzed, the video and audio recording will be destroyed. Collected data will be restricted to use by the researcher and locked into storage during required period for which the researcher must retain them. Breach of confidentiality is always a risk with data, but we will take precautions to minimize this risk as described in the confidentiality section.

Participants assigned to the AR WI will use a head mounted display (HMD) augmented reality headset to assemble a component. Using an HMD may cause minor temporary physical discomfort. To minimize discomfort, each user will be required to take 2-minute breaks after using the HMD for 15 minutes.

Are there any potential benefits?

There is no direct benefit to participants, however for the augmented reality participants, they may gain insight into the AR program and AR device.

Will I receive payment or other incentive?

You will be entered into a drawing where the researcher will give away 5 $20 Amazon.com e-gift cards. We estimate the odds of winning will be 1 in 10. Participants will not be qualified for the raffle if they do not complete all three sessions.

Are there costs to me for participation?

There are no anticipated costs to participate in this research.

This section provides more information about the study

Will information about me and my participation be kept confidential?

This study is internally funded by Purdue University's Digital Enterprise Center. Efforts will be made to keep your personal information confidential. Your identity will remain anonymous in reports of the study. Digital audio or video recordings will be made during the session, and after being anonymized and analyzed, parts of the recordings may be retained for data collection purposes in de-identified form. All other recordings will be destroyed. Any materials related to a study participant will be assigned a study-specific ID, and a code key will be maintained until all materials have been transcribed and coded with this ID. During the analysis process, digital recordings will be stored using a secure institutional repository. Only the researcher will have access to identifiable research records and data, which will be locked into storage during the required period.

The project's research records may be reviewed by departments at Purdue University responsible for regulatory and research oversight.

What are my rights if I take part in this study?

It is not a requirement to participate in this research project. If you agree to participate, you may withdraw your participation at any time during the data collection without penalty. If you choose to withdraw your participation, you will be able to exclude data that was collected from being used by the researchers. Your decision to participate or not in the research will have no effect on your relationship with your employer or other stakeholders.

Who can I contact if I have questions about the study?

If you have questions, comments or concerns about this research project, you can talk to one of the researchers. Please contact the primary investigator, Dr. Nathan Hartman at 765-494-4585.

To report anonymously via Purdue's Hotline see www.purdue.edu/hotline

If you have questions about your rights while taking part in the study or have concerns about the treatment of research participants, please call the Human Research Protection Program at (765) 494-5942, email (irb@purdue.edu) or write to:

Human Research Protection Program - Purdue University
Ernest C. Young Hall, Room 1032
155 S. Grant St.
West Lafayette, IN 47907-2114

Documentation of Informed Consent

I have had the opportunity to read this consent form and have the research study explained. I have had the opportunity to ask questions about the research study, and my questions have been answered. I am prepared to participate in the research study described above. I will be offered a copy of this consent form after I sign it.

_______________________________________   ________________________

Participant's Signature   Date

____

Participant's Name

_______________________________________   ________________________

Researcher's Signature   Date

APPENDIX C DATA

ID	WI Type	S1 Training time (s)	S1 Training time (m)	S1 Number of training cycles	S2 All errors	S2 Training time (s)	S2 Training time (m)	S2 Number of training cycles	S3 All errors
20	AR	956	15.93	2	1	333	5.55	2	0
21	AR	950	15.83	2	2	313	5.22	1	0
22	AR	646	10.77	1	1	335	5.58	2	0
23	AR	366	6.10	1	1	230	3.83	2	0
24	AR	977	16.28	2	0	0	0.00	0	0
25	AR	1015	16.92	2	0	0	0.00	0	1
26	AR	386	6.43	1	1	346	5.77	2	0
27	AR	421	7.02	2	0	0	0.00	0	0
28	AR	510	8.50	1	2	329	5.48	2	0
29	AR	372	6.20	2	0	0	0.00	0	1
10	3D PDF	585	9.75	2	2	115	1.92	1	0
11	3D PDF	409	6.82	2	0	0	0.00	0	2
12	3D PDF	739	12.32	2	2	93	1.55	1	2
13	3D PDF	335	5.58	2	0	0	0.00	0	0
14	3D PDF	257	4.28	3	1	137	2.28	1	2
15	3D PDF	426	7.10	2	3	90	1.50	1	2
16	3D PDF	234	3.90	1	0	0	0.00	0	1
17	3D PDF	313	5.22	2	0	0	0.00	0	0
18	3D PDF	464	7.73	2	0	0	0.00	0	0
19	3D PDF	651	10.85	3	1	125	2.08	1	0
30	Paper	355	5.92	1	2	146	2.43	1	0
31	Paper	839	13.98	3	1	102	1.70	2	2
32	Paper	679	11.32	2	1	163	2.72	1	2
33	Paper	329	5.48	2	3	249	4.15	1	2
34	Paper	302	5.03	2	0	0	0.00	0	0
35	Paper	547	9.12	2	0	0	0.00	0	1
36	Paper	590	9.83	3	2	133	2.22	1	3
37	Paper	824	13.73	2	2	151	2.52	2	0
38	Paper	507	8.45	2	1	203	3.38	2	1
39	Paper	673	11.22	3	0	0	0.00	0	1