School of Built Environment

Evaluating the Use of Augmented Reality to Facilitate Assembly

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signature: ……………………………….

Date: ……………………….....................

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This dissertation is dedicated to my parents, for giving me the strength of character to lead a righteous life. To my wife, for giving me the strength of will to pursue what I believed. Without them and all the sacrifices they have made, I wouldn’t have graduated from my studies.

The dissertation wouldn’t have been possible without my supervisors, Xiangyu Wang and Pete Davis. Xiangyu has been more to me than just an adviser in technical matters. A friend, a mentor, and a guide for life, he has given me the flexibility to pursue whatever I felt was appropriate, provided me with continuous guidance even beyond his areas of interest to help me work efficiently and remain focused, and given me the ability to form a vision to make the world a better place. Pete stepped in at just the right time to coach me, and without his continuous encouragement, inspiring dedication, and organised approach to research, I couldn’t have completed this dissertation. Xiangyu and Pete provided me with the perfect combination of advisers, more than I could have ever hoped to have as a graduate student.

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ABSTRACT

Lei Hou, Ph.D., Curtin University, February, 2013. Evaluating the Use of Augmented Reality to Facilitate Assembly. Major Supervisor: Xiangyu Wang; Co-Supervisor: Pete Davis

Assembly is the process in which two or more objects are joined together through particular sequences and operations. Current practice utilises two-dimensional (2D) drawings as the main visualisation means to guide assembly. Other visualisation means such as three-dimensional (3D) manual and Virtual Reality (VR) technology have also been applied to assist in assembly. As an emerging technology, Augmented Reality (AR) integrates 3D images of virtual objects into a real-world workspace. The insertion of digitalised information into the real-world workspace using AR can provide workers with the means to implement correct assembly procedures with improved accuracy and reduced errors. Despite the substantial application of AR in assembly; related research has rarely been explored from a human cognitive perspective. The limited available cognitive research concerning the applications of AR visualisation means in assembly highlights the need for a structured methodology of addressing cognitive and useability issues for the application potentials of AR technology to be fully realised. This dissertation reviews the issues and discrepancies in using four types of visualisation means (2D drawings, 3D manual prints, VR, and AR) for guiding assembly, and investigates potential cognitive theories to underpin the benefits of animated AR in assembly. A theoretical framework is then put forward, which summarises existing mechanisms concerning visual-spatial information processing and THE Working Memory (WM) processing in the context of spatial cognition theory, active vision theory and THE WM theory, and raises the to-be-validated aspects of the above theories when transferring from the psychological arena to practical instances. Moreover, the dissertation formulates the methodology of configuring a prototype-animated AR system, and devising particular assembly tasks that are normally guided by reference to documentation and a test-bed with a series of experiments.

Two experiments were conducted with three testing scenarios: experiment I concerns the evaluation in the first and second scenarios, while experiment II concerns the third scenario. In scenario 1, a small scale LEGO model was used as the assembly and experimental tester task to compare 3D manual prints and AR. This scenario measured the task performance and cognitive workload of using the system for assembly. The second scenario applied the knowledge gained from scenario 1 to the real construction piping assembly. Comparisons were then made as to productivity improvements, cost reduction and the reduction of rework between 2D isometric drawings and AR. Common findings from both scenarios revealed that the AR visualisation yielded shorter task completion time, less assembly errors and lower total task load. Evaluation from the real construction scenario also indicated that the animated AR visualisation significantly shortened the completion time (original time and rework time), payment to assemblers and cost on correcting erroneous assembly. Questionnaire feedback (including NASA task load index) (Hart 2006, 908) revealed that the animated AR visualisation better aided assembly comprehension, and better facilitated information retrieval and collaboration between human and guidance medium. Using the same LEGO tester task, the third scenario measured the training effects of using 3D manual prints and AR among novice assemblers. The results revealed that the learning curve of novice assemblers was reduced (faster learning) and task performance relevant to working memory was increased when implementing AR training. Useability evaluation was conducted based on classical useability methods, to assess the user interface regarding system improvements.

CHAPTER 1. INTRODUCTION

1.1. Background

Assembly is the process in which two or more objects are joined together. For instance, in order to achieve the apparently simple goal of placing a peg in a hole, a number of factors need to be considered, such as reaching for and grasping the peg, determining the relative positions of peg and hole, transporting the peg towards the hole, and inserting the peg accurately. Each of these actions requires differing levels of haptic and visual guidance. With its long history, assembly today is ubiquitous in many industries including manufacturing, construction and biomedical (Groover 2007; Gambao, Balaguer and Gebhart 2000; Tang et al. 2006). Manufacturing assembly, as one typical type of assembly, can be found in a wide range of mechanical products that are inseparable from everyday Western life, for example, cars, aircrafts, ships and computers. In the construction sector, assembly also applies to the formation of construction materials, such as Heating Ventilation Air Condition (HVAC) piping assembly, rebar assembly, prefabrication assembly and concrete formwork assembly. Biomedical assembly, originally emerging as a novelty, has now widened the concept of assembly into nano-assembly of polymers, enzymes, and nanoparticles (Such, Johnston and Caruso 2010, 26).

The above mentioned examples have illustrated the significance of the applications of assembly. From a technical perspective, how to soundly frame the craft of guiding assembly operations is one of the critical issues to be resolved. This includes the detailing of investigations as to draft assembly sequences, reduce assembly tolerance, and optimise assembly methods. In addition, advancing the performance of assemblers is another critical ergonomic issue. This refers to improving task proficiency, reducing time consumption, lowering error rate and stimulating task motivation. As technology advances, robots are taking over more and more of the work that used to require human operators, resulting in better quality and productivity. However, automation and machines cannot provide the complete flexibility of assembly that a human can and therefore complete automation may not necessarily be possible within certain work contexts (Feldmann and Junker 2003, 1; Säfsten, Winroth and Stahre 2007, 30). For instance, it is more appropriate to conduct complex assembly tasks manually, such as watch assembly and cable assembly, small scale assembly tasks requiring human fine motor skills and small-batch cost-limited assembly tasks. Everett (1994, 443) also revealed that automation is more suitable for physical tasks which can be done by machine whereas humans are still more cost effective at information-intensive tasks that require judgment, sensing, and adaptability. Given that the need for human assembly will continue into the foreseeable future, it is pertinent to examine the problematic issues that exist within this area.

In most professional assembly practices, two-dimensional (2D) paper-based drawing is typically used to guide the tasks required to put together an artefact. The drawings provide a list of parts, identify those parts by number and show how different parts go together. They show the assembly information associated with the separate components/parts, providing the essential technological reference for assemblers to enact assembly, conduct assembly tasks, review assembly steps and evaluate the final results. A well-formulated assembly drawing should possess, at minimum, the following assembly information: visual perspectives of components, parameters or dimensions, technical requirements in quality, installation and testing specification, and other auxiliary information. In the manufacturing/construction industry, assembly drawing is the technical drawing of composite buildings/products that fall within the definition of its architecture. The drawings are used by architects and engineers for a number of purposes: to develop a design idea into a coherent proposal, to communicate ideas and concepts, to convince clients of the merits of a design, to guide an assembler to assembly, and a record of the completed work. Assembly drawings are drawn according to a set of conventions, which include particular views (top view, front view, side view, and section view), sheet sizes, units of measurement and scales, annotation and cross referencing. However, many shortcomings have been found from this visualisation means. For example, considerable mental activity is required to understand the assembly-relevant details based on 2D drawings as they are not conducive to an intuitive understanding of relationships between different views. Once developed, they are not easy to modify should the assembly process change. Attempts to concentrate large amounts of information in 2D drawing context can result in misinterpretation and misunderstanding, particular for the novice assembler who has limited experience. Another visualisation means for guiding product assembly is the three dimensional (3D) manual (handbook), generally used in guiding the ordinary user in assembling customised products. 3D is intuitive, easy to understand, and does not necessarily need to contain complex context, compared with 2D assembly drawings.

With the swift development of computer technology, particularly the development of computer visualisation and simulation, the application of Virtual Reality (VR) technology is becoming more prevalent. As a well-established class of visualisation technology, VR has been investigated for decades for its ability to facilitate assembly tasks and has been used extensively in the assembly of products (Ritchie et al. 2007, 262). Product designers are able to create virtual prototypes for accessories, modules and parts in Virtual Environments (VEs). Trial assembly in a virtual environment enables problematic tasks to be identified and various assembly methods to be explored. Commercial VEs prototyping software such as Computer Aided Design (CAD), Pro/Engineer and IDEAL has been widely used to facilitate the product assembly and design process. Product technicians are also capable of designing and developing various product accessories, modules and parts with different functions and dimensions and conducting the assembly guidance in a virtual space. There are more applications for using VR technology in guiding assembly in manufacturing, but fewer in construction. Most VR applications in the construction sector are reflected in construction design (creating 3D virtual environment where people are involved with a view to achieving a full range of dynamic interaction), They are also used in the execution of construction work (simulation test, risk evaluation and decision making), as well as building renovation (decorating and modifying virtual rooms according to the users' own ideas to such as observing the decorative effects).

Augmented Reality (AR) technology, a more expansive form of VR (Azuma et al. 2001), has also broadened the trial of new technology in the assembly arena (Figure 1). AR allows an assembly worker to work in a real-world environment while visually receiving additional computer-generated or modelled information to support the assembly task at hand. Previously, AR environments had been applied primarily for entertaining, purely in a visualisation context. In recent years, they have been explored for goal-oriented human activities like assembly guidance, assembly training and collaborative work (Schwald and De Laval 2003, sec. 4: Augmented Reality in Industry). AR has received a great deal of attention and it is the focus of the research discussed in this dissertation. The introduction of AR technology and more practical engineering and construction applications of AR assembly can be found in the comprehensive survey presented in the next chapter.

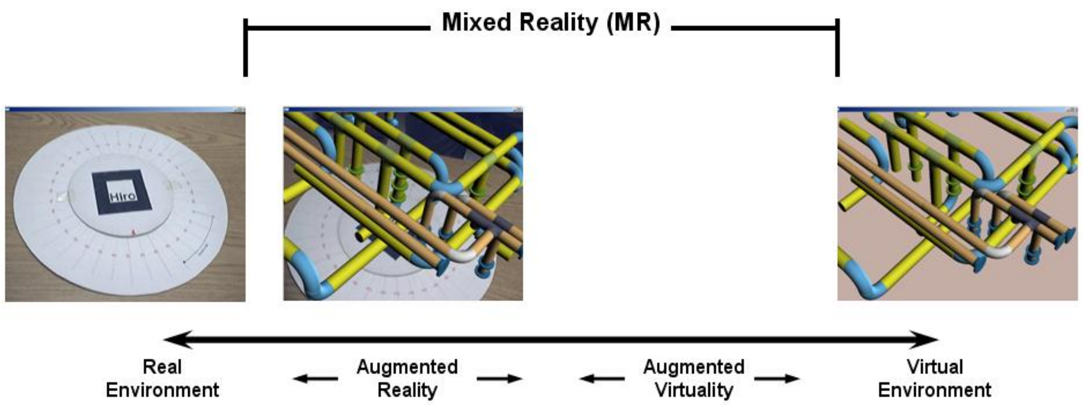


Figure 1. An Example of Using AR Technology as Visualisation for Viewing Piping Assembly (Wang, Xiangyu 2006, 3)

1.2. Statement of the Problem

The implementation of assembly tasks based on 2D drawings typically consists of work and non-work-piece-related activities (Neumann, Ulrich and Majoros 1998, 4). In each assembly step, the assembler is required to conduct a series of physical operations (observing, grasping, installing) and mental manually-related processes (comprehending, translating and retrieving information in context) (Neumann, Ulrich and Majoros 1998, 4). Ulrich Neumann and Majoros (1998, 5) have also suggested that information-related activities tend to be cognitive whereas work-piece-related activities involve kinesthetic and psychomotor skills. These are so connected together that it is easy to overlook the impact of information-related activities on direct work performance. The skills and abilities for these two activities are very different, and they are often summoned sequentially. Towne (1985) has suggested that using drawings in assembly consumes a large amount of ‘invalid time’ (time consumption irrelevant/unrelated to work-pieces). Moreover, Towne (1985) suggest that the process of assembly based on planar drawings fails to consider the cognitive issues as well as the large number of switchovers between physical (work-piece-related) and mental (manual-related) processes. These can result in operation suspensions and attention transitions occurring in novice assemblers. The time-consuming nature of activities has been identified by Towne (1985), who found that information-related activities (cognitive workload) accounted for 50% of the total task workload. Similarly, Ott (1995) revealed that 45% of every assembler’s shifts were actually spent on finding and reading procedural and related information when assembling hardware that had been repaired. Ulrich Neumann and Majoros (1998, 4) identify that individual technicians differ in how much time they devote to cognitive/informational chores, but demonstrate marginal differences with respect to operational tasks. The use of an assembly drawing for complex and intricate processes can contribute to mental tiredness and the propensity to commit errors as information retrieval increases. Likewise Veinott and Kanki (1995) revealed that 60% of errors that are committed are procedural and are due to misunderstanding the drawing. Such misunderstanding may arise due to the unilateral retrieval of information which may trigger behavioural repetition and therefore suppresses motivation.

The above issues are mainly due to the fact that an assembly drawing is typically paper-based and contains a large quantity of information pertaining to product parts/components, and much of this information may be redundant, particularly for complex tasks. As a result, this may hinder an assembler's information orientation and their ability to understand complex assembly relations. It is widely accepted that the capacity for selective information retrieval and filtering does not occur until assembly experiences and expertise are acquired, thus, extra targeted training activities may sometimes be needed (Agrawala et al. 2003, 828). Using an assembly drawing does not necessarily provide an assembler with the problem-solving skills that are often required when putting together components. In some cases, an expert assembler must constantly refer to the assembly drawings for unfamiliar procedures or procedures that are deemed to be arduous. Therefore, it is advantageous to find better solutions as alternatives for conventional 2D assembly drawings.

As an alternative of traditional 2D assembly drawings, 3D visualisation has emerged as an aided means for guiding assembly tasks. 3D visualisation means can be realised using artificial 3D images (3D assembly manual) and computer-generated 3D models (VR). However, there can be drawbacks. Some assemblers may be somewhat over-confident and/or have little time to spend with 3D assembly manual prints. Other influencing factors include the quality of the manual which often may not be satisfactory. In addition, different people have different levels of expertise and therefore require a different set or type of instructions. Another reason why 3D manual prints can frustrate the reader is where problems arise and specific instructions or solutions are sought from the manual immediately. 3D instructions should be usable as reference manuals, but in such a format that they suit the expert as well as the complete beginner. Another important limitation with today's 3D manual prints is their mostly linear format; they describe only one way to complete task. For a beginner this might be appropriate, for other more advanced, this format can be restrictive and frustrating. 3D instructions are still mostly static and not adaptable to the state of the environment and the user. Compared to the 3D assembly manual, the advantage of 3D visualisation in VR is that it attempts to replace the user's perception of the surrounding world with a spatial layout and 'intuitive' view of components. Due to its artificial nature, one critical defect is that VR cannot provide a better understanding of diverse interferences with the assembly path in real assembly environments. Issues such as assembling difficulty and workload cannot easily be evaluated either (Wilson 1999, 6). Regardless of the accuracy that can be acquired by using VR in product assembly, errors and defects can still arise. VR attempts to replace a user's perception of the surrounding world with computer-generated artificial 3D VEs. However, VEs are unable to account for the diverse interferences such as weather, labour constraints and the schedule pressure which can arise during the assembly process within the real-world. In addition, computer-generated dimensions, textures, spatial location and backgrounds provide a limited level of 'realism' due to a lack of sensory feedback and are therefore unable to allow for perceptual and cognitive viewpoints. The lack of interaction between virtual and real world hinders the adoption of VR for product assembly tasks.

In order to make the means of visualisation more dynamic and adaptable to the current situation, AR has been identified as a solution to addressing the problem between the virtual and real entities (Azuma et al. 2001, 34). This is where AR technology enters into the arena from a cognitive psychology standpoint. AR has the potential to merge informational activity with the direct work activity, thereby allowing information access more efficient and therefore completely changing the way we think about and use instructions. As an emerging technology, AR integrates images of virtual objects into the real world. By inserting the virtually simulated prototypes into the real world and creating an augmented scene, AR technology could satisfy the goal of enhancing a person's perception of virtual prototyping with real entities. This gives a virtual world an ameliorated connection to the real world, while maintaining the flexibility of the artificiality of the virtual world. While VR separates the virtual from the real-world environment, AR maintains a sense of presence and balances perception in both worlds. Through AR, an assembler can directly manipulate the virtual components whilst identifying potential interferences between to-be-assembled objects and existing objects inside the real environment. Therefore, in an AR environment an user not only interacts with real environments, but also interacts with Augmented Environments (AEs) that are structured to offset partial sensory loss that may be experienced within VR. Furthermore, to improve the feedback of augmentation, additional 'non-situated' elements could be added into the assembly process such as voice recording, animation and video. With this in mind, the reality being perceived is further augmented.

In next chapter, several AR studies are reviewed. While these studies have made a significant contribution to understanding the product assembly process, several key issues remain unresolved within the assembly domain. For example, the majority of research work in AR for assembly focuses on technical implementation and proof-of-concept. Researchers have yet to acquire an in-depth understanding of an assembler's cognitive workload when using AR as an alternative to manual procedures and VR. The images of the 'to-be-assembled' objects in AR systems only reflect their bilateral or multilateral positioning, and thus do not take into their account the dynamic context (e.g., displacement path and spatial interference). To acquire the information in the appropriate context, such as the assembly path and fixation forms of parts/components, assemblers are often required to rely on memory retrieval after being subjected to static augmented cues.

It is noted that a very low percentage of general AR research work involves significant and scientific evaluation component, as with AR prototypes. Unfortunately, even less evaluation work is deemed relevant to assembly. Generally, there are two classes of evaluation: effectiveness evaluation and useability evaluation. Effectiveness evaluation concerns the ergonomic improvement, performance time, number of errors, and other quantitative indicators of how effectively a particular AR system can facilitate a certain task or activity. Useability category involves investigating user needs based on user interviews, field evaluations with users and expert evaluations of the AR system. To further subcategorise the evaluation work, there are two types: self-evaluation and comparative evaluation. Self-evaluation, which evaluates the effectiveness and system performance itself, has been commonly conducted. However, comparative evaluation has rarely been researched (comparing the AR tool with a well-established benchmark, e.g., a typical work method/tool). Since comparative evaluation is deemed fair and objective, it is a procedure worthy of inclusion\.

1.3. Aim and Research Objectives

The abovementioned has confirmed that the majority of the relevant work in AR has focused on proving the viability of the concept of using AR technology itself. Very few noted empirical works have assessed how much workload can be alleviated, how many errors can be reduced and how much the learning curve can be improved when using AR visualisation means as assembly guidance or as a training tool. Therefore, the methodology of this research is based on comparative evaluation (setting the commonly-used 2D assembly drawings vs. 3D manual prints as comparison benchmarks). The aim is to experimentally validate the benefits of using animated AR visualisation in assembly work in two aspects: (1) the improvements/facilitations that the animated AR visualisation could lend to the assemblers in terms of task performance and cognitive workload and (2) how AR can help novice assemblers learn faster (shorten the learning curve). This dissertation brings forward six particular research objectives for the timeline of this research, as depicted in Figure 2.

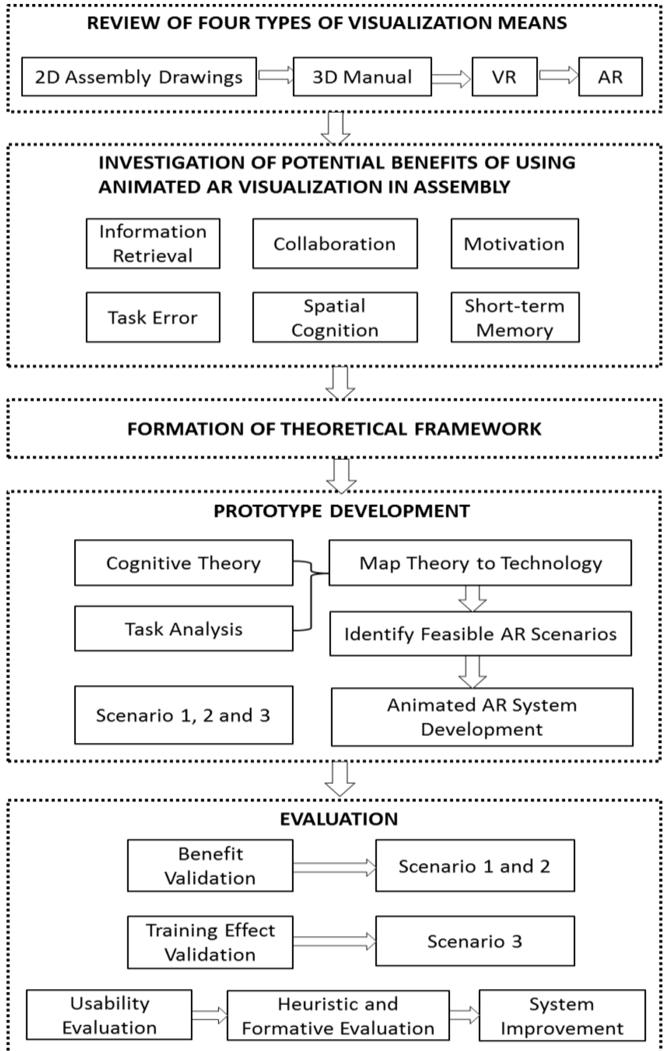


Figure 2. Research Framework

- Review the current visualisation means (2D drawings, 3D manual prints, VR and AR) in assembly.
- Summarise and analyse the potential underpinned theories concerning visuo-spatial information processing and the WM processing in the context of spatial cognition theory, active vision theory and the WM theory. Develop the

theoretical framework to validate the to-be-validated aspects of above theories when transferring from psychological area to practical instance (hypotheses).

- Devise three particular assembly scenarios that are normally guided by traditional visualisations (3D manual prints/2D isometric drawings) and testable with two experiments. Prototype the animated AR system in aiding small scale and real scale assembly.
- Develop a comparative methodology (a comparison between AR and 3D manual prints/2D isometric drawings) to experimentally evaluate the effectiveness of AR in terms of assembly guiding and training.
- Quantitatively and qualitatively verify that the animated AR visualisation can be used as an effective alternative to traditional visualisations.
- Implement heuristic and formative useability evaluations of system improvement suggestions for enhancing animated AR for future use in real projects.

1.4. Dissertation Organisation

In the following chapters, Chapter 2 presents a literature review regarding the foundations for this research. Chapter 3 puts forward the potential benefits of using animated AR visualisation in assembly, as well as the theoretical foundations. Chapter 4 raises the research questions and hypotheses. Chapter 5 develops a thorough methodology of experimental design for evaluating on-task performance, on-task cognitive workload and post-training learning curve, mapping appropriate AR technology to specific assembly tasks, and investigating useability issues of AR system. Chapter 6 analyses the data from two scenarios in three experiments. These were designed to validate the effects of using the animated AR system for certain scenarios over traditional 2D drawings and 3D manual prints. Chapter 7 presents the useability evaluation methodology and the associated useability issues. Finally, Chapter 8 presents a summary of the completed work and recommendations for future research.

CHAPTER 2. REVIEW OF VISUALISATION MEANS IN GUIDING ASSEMBLY

2.1. 2D Assembly Drawings

Drawings in building construction are produced for specific purposes, and accordingly the sets of drawings can be classified such as building arrangement drawings, assembly drawings (Figure 3), detail drawings and fabrication drawings. Maguire and Simmons (1995, sec. 1: General Arrangement Drawings) stated that as for the assembly drawings, the information context should include self-contained units that make up the product, i.e., a table of parts, fabrication and detail drawings, overall dimensions, weight/mass, lifting points, information on construction, tests, lift, transport, and installation. Most importantly, assembly drawings should clearly detail how the construction components are assembled. In building construction projects, a comprehensive set of assembly drawings typically shows the general arrangements of different architectural parts and how the different parts are put together. For example, details about constructing a wall in a building should show the layers that make up construction, and how the layers are assembled with the structural elements, how to finish the edges of openings, and how prefabricated components are to be assembled. Construction assembly drawings typically combine plans, sections, elevations and details on a sheet, to provide a complete explanation of a building. Constant reference to 2D drawings during the course of performing assembly activities is a common practice and accepted as a necessary part of the work.

The traditional way that humans access information starts with directing one's attention to a storage medium such as a paper drawing, where humans read, comprehend, and calculate if necessary, the required information. Hypotheses, which are used to transpose the interpreted information from documents to actual work, are then formulated in the individual's brain. The associated information is memorised in the human brain, and this can be retrieved from the memory while performing the physical work activity. The development of computer technology has had a major impact on the methods used to design and create assembly drawings, and the vast majority of assembly drawings are created using CAD software. The advantages of computer-aided assembly drawings are obvious: complex content and context can be expressed, design errors can be detected and modified, and accuracy can be increased. Although 2D CAD assembly drawings are still commonly used, the complex curved faces are not easy to express or understand through the three views of 2D assembly drawings. Therefore, an important task is to convert 2D models to 3D models. Previously, this was usually carried out manually even in some of the CAD systems. Tanaka et al. (1998) proposed a unique method to automatically convert 2D orthographic assembly drawings to 3D part drawings using modern CAD systems, regardless of the complexity of the original models. The only requirement for the approach was that the assembly drawings consisted of standard parts such as bars and plates. Based on this, further research work has focused on modifying or redesigning the complex 3D architectural part drawings. Lu et al. (2005, 527) proposed a new method for accurate 3D reconstruction from real-life architectural assembly drawings, which integrated and normalised the architectural information dispersed in multiple drawings and tables under the guidance of semantics and prior domain knowledge. It is even more remarkable that in their work, the reconstructed detailed 3D models could be used for quantity surveying and the generation of 4D models.

To meet the need for cultivating the talents of assemblers in application-type modern assembly fields, a new teaching and training system of the assembly manual was constructed (Wang, Jinyu, Hao and Yu 2010). The manual was capable of stimulating an assembler's enthusiasm for learning assembly operations and for training their spatial thinking capacity for effective operation. This system integrated the contents of teaching theory, learning theory and assembling/dismantling principles, and investigated a diversity of assembly teaching methods. Based on an experimental study, this system has been proven to be highly effective in tutoring novice assemblers. More relevant research concerning drawing training and/or cognitive ergonomics analysis of assembly training can be found in the work of Hollands and Wickens (1999, chap. 7) and Thorvald et al. (2008).

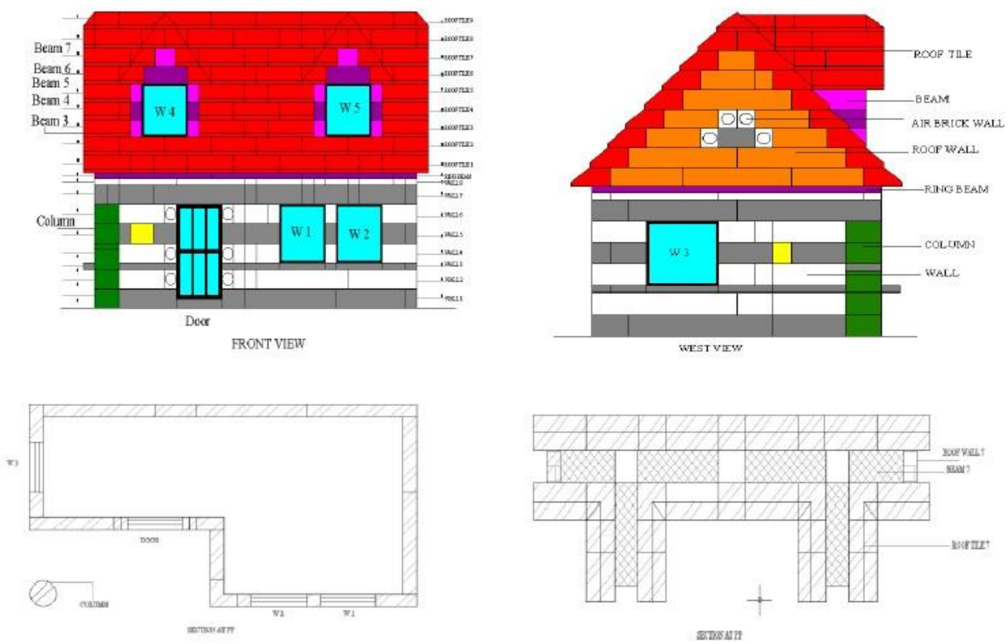


Figure 3. An Example of a 2D Assembly Drawing: Two Views and Horizontal Sections of LEGO Building Model (Dawood and Sikka 2008, fig. 3)

2.2. 3D Assembly Manual

Today, 3D visualisation means has been widely used in numerous examples of everyday product assembly (e.g., IKEA products). Many modular products, such as furniture, appliances, and toys, require assembly at home. Included with each product is a set of assembly manuals, many of which are usually presented in the form of 3D images and printed out in assembly manual or handbooks, showing how to put the product together (Mijksenaar and Westendorp 1999). This visualisation means is popular as it integrates the 3D assembly or detaching instructions themselves into the object or environment of interest. A relevant and interesting example is the way in which photocopiers present instructions to resolve paper jamming issues. Whenever a problem occurs they display just-in-time 3D instructions for immediate assistance in dismantling certain components (Tsusaka 2006). Another example is the work of IBM, called 'out of the box experiences', where the different steps of assembly (for example of a laptop) are printed as 3D images in a paper-based manual for the user to perform an assembly operation (Antifakos, Michahelles and Schiele , quoted in Selker and Burleson 2000, 880). 3D assembly manuals have obviously drawn considerable attention; they guide the everyday assembly of products and are optimised to be unambiguous for and understandable to the broad range of educational levels found in a population (Antifakos, Michahelles and Schiele 2002, 10).

Since the construction industry is constantly seeking more sophisticated information , the importance of sharing and communicating information is becoming increasingly important throughout the life of a construction project. Unfortunately, extraction, interpretation and communication of complex design information based on 2D drawings is time-consuming and difficult. In order to overcome this bottleneck, a promising trade-off is in developing proper visualisation technology and displaying information to assist in the understanding and evaluation of information. However, being described as a slow adapter of new technology, the construction industry has attracted only a few research works in developing visualisation technologies. Dawood and Sikka (2008, fig. 3) applied 3D visualisation technology to measure the effectiveness of communicating the information on a construction product and the interpretation ability of project team members using 3D visualisation, compared with traditional 2D drawings. Using experiment-based methodology, they evaluated and compared the effectiveness of communication and the capacity of assembly information interpretation among different age groups in two different visualisation scenarios: 2D paper-based assembly drawing and a 3D laptop-based assembly manual. Quantitative outcomes revealed that the 3D group performed better than the 2D group. For example, the 3D group was 7% faster assembling the physical model, spent 22% less time in extracting information from the building information, and assembled 23% more building pieces. Qualitative outcomes also suggested that that 3D group was able to communicate and coordinate more efficiently, and that 3D technology can facilitate a better understanding of building information. As the availability of custom-built products increases along with the demand for task specific instructions, technology is needed to produce assembly instructions more cost effectively (i.e., less time-consuming and less labour-intensive). Unfortunately, the process for designing assembly instructions has not been systematised, thus only skilled human designers are able to produce appropriate instructions. In order to creating cost-effective assembly instructions, Agrawala et al. (2003, 829) have reviewed the principles of cognitive psychology research and investigated people's conceptual models of assembly along with effective methods to visually communicate assembly information. Exploring the algorithmic techniques grounded on the given object's geometry, orientation, and optional grouping and ordering constraints on the object's part, they have created a system for automatically producing cost effective 3D visualisation based on assembly manual prints. System evaluations have demonstrated that this system was able to produce aesthetically pleasing and easy-to-follow instructions for a variety of everyday objects.

2.3. VR Visualisation

Described as a technology for which 'the excitement to accomplishment ratio remains high' (Durlach and Mavor 1995, 14), VR is rapidly outgrowing its computer games image and finding applications in a variety of fields as diverse as engineering (Bierbaum et al. 2001), design (Sherman and Craig 2003), architecture (Sala 2006), medicine (Cates et al. 2007), education (Mantovani 2001) and the military (Gerardi et al. 2008). The kernel of VR is computer simulation, which combines three-dimensional (3D) graphics, motion tracking technology and sensory feedback (visual, haptic, auditory). Accordingly, VR attempts to replace the user's perception of the surrounding world with computer-generated artificial 3D VEs. The use of VEs allows the total control of both stimulated situations and the natural pattern of feedback, and also allows the comprehensive monitoring of performance. To date, there are already various well-known applications of VR technology. One of the most famous applications is NASA's Hubble Space Telescope repair mission, where immersive VEs were created to train telescope repair personnel (Veinott and Kanki 1995). Another is found in a U.S. military project, where the networked artificial VEs were aggressively pursued for the distributed simulation of integrated combat operations. In this project, the diverse topographic and climate elements were mixed together by creating a series of complex scenarios comprising both real and autonomous agents (Mastaglio and Callahan 1995). Rose et al. (2000, 494) also found that VEs had a considerable skill transfer effect in implementing training task. According to their experiments, the performance of trainees resulted in an equivalent extent of skill transfers from training in VEs to real post-training tasks and from training in real environments to real post-training tasks.

To further propel the applications of VR technology in the manufacturing and construction industries, several technical challenges have been researched, namely: component collision detection (Burdea 2000, 295), assembly path accessibility (Frohlich et al. 2000, 5), virtual component manipulation (Seth et al. 2005, 3) and data transfer between CAD and VR systems (Wang, You et al. 2003, 231). Some examples of VR applications in manufacturing are: Sun and Cao (2010) imported the models of a cotton picker roller into the VR assembly scene, added virtual hands to interact with the virtual components of the roller, realised the assembly path visualisation, provided a set of adequate operation guides for workers, and finally, effectively carried out the assembly process of the cotton picker. Immersive VR technology was also applied in the domain of cable harness assembly by Ritchie et al. (2007, 262). The aim of their work was to understand the degree to which various aspects of their CAD-equivalent VR system were contributing to the productivity of cable harness assembly and how the ergonomic issues in this process could be analysed in detail. They carried out a set of creative design task experiments for detailing the VR system's advantages and human performance improvements, using the scenarios of cable harness routing design, assembly and installation. The results from experiments showed that substantial amounts of time were saved. Percentage wise, 41%, 28% and 27% of time was allocated respectively to spreading in component navigation, sequence breaks and carrying out assembly-related activities. This can be interpreted as advantageous in terms of time saving, compared with the traditional means of conducting assembly tasks. There are other instances of successful examples of the use of VR in assembly teaching and training. Sanz et al. (2011, 119) incorporated VR technology into teaching assembly learners to assemble numerical machines, showing that it is possible to supplement ordinary teaching practice, as well as transforming a cumulated training experience through virtual assembly operations that are similar to real operations, while eliminating the risks of use for both users and machines.

One of the potential advantages of virtual assembly training over conventional training practices is that it is adaptable to desktop-based computers/laptops, thus desktop-based VR assembly training attracts much attention from the manufacturing industry. Other advantages include significant cost savings, which can be realised due to shorter training-scenario development times and the reuse of existing engineering models; the time span from training novice to expert can be shortened due to non-reliance on hardware parts. Bhatti et al. (2008, 1) presented a haptically-enabled interactive and immersive VR (HIIVR) system that provided comprehensive user interaction and constrains within the physical limitations of the real world imposed by the haptics devices. As a result, in contrast to existing VR systems which are capable of providing basic knowledge about assembly sequences only, this training system helped in procedural learning and procedural skill development, due to its highly physical interactive nature.

Although a large number of digital technologies have been developed to visualise innovative manufacturing assembly, few VR systems have been developed to facilitate assembly visualisation of the construction plans of building projects. In reviewing the limited available literature, Pyo et al. (2008, 1471) conducted examinations onto One-Touch Extension (SOTE), a polyethylene drainage pipe fitting assembly process, carried out via virtual assembly. Within their work, the SOTE polyethylene drainage pipe fitting was virtually assembled to examine design efficiency and performance, and the corresponding experimental results were compared with the predicted results. Three conclusions affirmed the feasibility of using VR technology in examining the structural soundness and thermal deformation behaviour of the construction of the SOTE fitting assembly. Through virtual assembly, using the finite-element method, the convenience of insertion and structural feasibility were verified, the proposed SOTE fitting was predicted to be actively able to cope with thermal deformation in spite of the high thermal expansion coefficient of the polyethylene, and under the fatigue load, the fitting malformed up to certain point but it could be rapidly resume to almost its original state, providing the structural integrity of the SOTE design. Lu et al. (2010) conducted a pipe layout design and assembly planning method in VE, and a controllable model was put forward. The model was based on a control point description to achieve its controllability. Using VEs as the design carrier, this method eased the processes of designing pipe layouts, assembling, and assessing the installation effects before it would be formally put into use.

Another advantage of VE is that the virtual pipe under is easy to edit or rework. To reduce material waste generated by incorrect layout results, a method of integrating layout work and assembly planning was brought forward to support field production. Haas and Fagerlund (2002) recognised the importance of integrating VR technology and the possibility of its application in modular construction. They also claimed that visualisation enhancement provided by VR technology could assist engineers in assessing complex assembly modules for efficient assembly in terms of fabrication and installation. Kadhim et al. (2009, sec. 2.3: Opportunity of VR Application in Modular Construction) stated that VR allows for effective communication with task participants in concurrent assembly projects, since the distribution of information and the mutual communication among task participants can be enhanced under the VR interface.

However, the loss of ‘sense of self’ in VR has often resulted in participants feeling disoriented and having difficulty in human movement and intended behaviours in operating assembly tasks in VEs. In other words, in order to rotate or move a virtual object, the person must cognitively ‘transform’ these operations into 1) move mouse cursor over appropriate button; 2) click button; 3) see object orientation change and 4) process the result in order to create additional mouse clicks. This brief list is greatly simplified to explain the complicated cognitive and motor processes needed in order to make a virtual object on desktop change its orientation. The point is that such processes may inhibit the acquisition of visual information. The active vision theory (Aloimonos 1993, 18), as detailed in the next chapter, advocates the direct physical manipulation of an object for the effective computation of object recognition as well as eventual understanding in accordance with this recognition. Fortunately, the physics-based simulation of VR visualisation has already attracted research interest in virtual manufacturing for product assembly and disassembly (Aleotti and Caselli 2011). In the previously mentioned work, the potential benefits of physics-based modelling for the automatic learning of assembly tasks and for intelligent disassembly planning in VR were explored. This was to examine where assembly/disassembly learning and reasoning at the physical level facilitates the discovery of assembly task similarities under VR visualisation means. Aleotti and Caselli (2011) applied a novel physics-based modelling technology to resolve disassembly sequence planning issues and this technology allowed computation of all the physically stable subassembly configurations and all the possible destructive disassembly sequences of a set of objects. Moreover, they proposed some strategies via precedence relations, assembly demonstrations and geometrical clustering, aimed at reducing the computational time required for the physics-based VR visualisation to plan the disassembly process.

2.4. AR Visualisation

Defined as the combination of real and virtual scenes, AR has been explored in a number of applications in areas such as maintenance (Toro et al. 2007), manufacturing (Doil et al. 2003), training (Blum et al. 2009), medicine (Behringer et al. 2007), 3D video conferencing (Regenbrecht et al. 2004) and entertainment (Oda et al. 2008). In AR, the person is able to combine the 3D object into the normal viewing perspective without losing any of their advantages of object movement and individual movement that creates the behaviours that help us perform activities (gain sensorial-based knowledge) in real-world environments. AR appears to be a compelling environment in which to engage spatial phenomena: the retention of proprioception and the retention or sensorimotor function. In AR, the participant retains the proprioception of self within the environment. That is, the unconscious awareness of one's own physical presence in space remains intact. Often VEs neglect the idea of representing the participant's physical space in the environment, instead relying on a smaller representation as an avatar or glove that 'floats' in space without a parallel representation of the body of the participant. With AR, the action within the environment is created by physical movements initiated by the participant. Other sensorimotor processes of temperature and texture, audio and olfactory senses all remain true to the encoding of implicit knowledge. Artificial sensory feedback of the environment such as force-feedback mechanisms in peripheral devices is no longer necessary.

Some successful AR applications in industry are: Webster et al. (1996) presented AR systems to improve methods for inspecting architectural structures. Wearing a head-mounted display (HMD) to overlay graphics and sounds over one's naturally occurring vision and hearing, the subject was able to see the location of columns behind a finished wall, the location of rebar inside one of the columns, and a structural analysis of the column. Roberts et al. (2002) used AR to overlay locations of subsurface electrical, telephone, gas, and water lines onto real-world views. Both applications demonstrated AR's potential in helping maintenance workers avoid buried infrastructure and structural elements as they make changes to buildings and outdoor environments. Another successful application is in integrating AR with manual gas-metal-arc welding technology. Traditionally, the welder has a very limited field of view through the dark cartridge used to protect their eyes from dangerous UV radiation. Hillers et al. (2004) applied AR registration technology to the welding helmet to aid the welding process by virtually presenting the outline of to-be-welded objects. The new welding helmet combined AR system—TEREBES (Tragbares Erweiter tes Realitäts-System zur Beobachtung von Schweißprozessen System), which is a wearable AR system for observing welding processes. Through TEREBES, limited real vision was enlarged by virtual vision and the welders could conduct the overall welding performance with greater ease. Another successful application of using augmentation is factory layout planning. Volkswagen has developed an AR-supported manufacturing and planning system where the physical production environment can be superimposed with the virtual planning objects, and the planning tasks can thus be validated without modelling the surrounding environment of the production site (Doil et al. 2003, fig. 4). By combining and superimposing the result of the ergonomic simulation process, planners can optimise the manual workplace without actually modelling the workplace. During this process, production personnel can participate and various rearrangements can be benchmarked at the same time.

Current AR technology has also attempted to create a novel car racing game, in which virtual objects are overlaid on the real world, and real objects are tracked and used to control virtual ones (Oda et al. 2008). This game is distinct from traditional computer games (which typically lack immersion and tangibility); it realises an open interface between virtuality and reality and enables a tangible controller based on the real driving controller and rotatable markers. It is also easy and fast to experimentally modify game functionality via vision tracking and non-driver player interaction.

In order to obtain an optimised assembly sequence, Raghavan, Molineros and Sharma (1999, fig. 4) adopted AR as an interactive technique for the assembly sequence evaluation, and formulated the assembly planner and liaison graph. In their research work, they addressed the issue of automatically generating the most optimised product assembly sequence in AEs. Similar research work can be also traced from Liverani, Amati and Caligiana's project (2004, fig. 6), where a binary assembly tree (BAT) algorithm was developed with the personal active assistant system (PAA). The BAT in PAA replaced the function of the liaison graph and shaped an assembly sequence optimisation method of their own to aid the product assembly design. At the same time, an inline assembly database was created as an attachment of the PAA system. AR has been identified as a key technology that can be used to improve the product assembly process as it can take into account human cognition (Salonen et al. 2007, 122). For example, Salonen et al. (2007) used a multi-modality system based on the commonly used AR facility, an HMD, a marker-based software toolkit (ARToolkit), image tracking cameras, web cameras and a microphone to examine the industrial product assembly. Their system realised an intelligent user interface and this interface enabled three controlling methods to effectively process the assembly design of industrial products, the keyboard control, the gesture control and the speech control. Many past AR developments were based on the ARToolkit, a powerful agent for object registration. Making use of the ARToolkit, the users could register virtual images of product components onto predefined markers and view them through monitors like HMD or a computer screen using a marker tracking camera. However, the marker registration technology limited the presentation of augmented clues. Xu, Chia and Cheok (2008) developed a markerless-based registration technology to overcome the inconveniences of applying markers as carriers in the assembly design process. Despite the development of a markerless-based AR system named *real-time 6DOF camera pose tracking system*, this still did not thoroughly overcome the related technical limitations such as radial camera distortion and perspective projection. AR technology has also been used extensively in the assembly design of a wide range of products, e.g., furniture (Zauner et al. 2003) and industrial robots (Yamada and Takata 2007).

Various AR applications can be found in the construction industry. However few of them are contextualized in terms of the assembly aspect of construction. Hammad, Garrett and Karimi (2004) augmented contextual information on real views of bridges to help inspectors conduct inspections more effectively. Klinker et al. (2001) explored AR to visualise power plant designs outdoors. Behzadan and Kamat (2005) investigated the use of AR to animate construction at the operations level in outdoor environments. To explore the suitability of AR applications in industrial construction, Shin and Dunston (2008) also presented the assessment research from the viewpoint of human factors regarding visual information requirements to identify construction tasks to which AR visualisation can be applied for better performance. This research confirmed the potential benefit of using AR visualisation in eight classified construction tasks: layout, excavation, positioning, inspection, coordination, supervision, commenting, and strategising. AR visualisation has also widened its feasibility in evaluating earthquake-induced building damage. Kamat and El-Tawil (2007) proposed an approach to quantify structural damage by measuring and interpreting key differences between real and AR visualisations of the building. Experiments highlighted the potential of using AR for rapid damage detection and as an indicator for measuring structural displacement induced by earthquakes.

Considering that current practice for heavy equipment operator training is predominantly limited to: 1) off-site training programs that give the novice a limited opportunity to experience real working conditions and 2) on-the-job operator training which is not only costly but is often not possible, requiring specialised equipment and an on-the-job trainer. Xiangyu Wang and Dunston (2007) proposed the potential of using AR in construction equipment operation and operator training. Based on the AR-based real-world Training System (ARTS) that can produce virtual materials and instructions, they presented a real worksite environment, constructed on AR visualisation for training novice operators in information-intensive tasks. The evaluation of their field training tasks concluded that the ‘embedded’ training characteristic of ARTS inside the real worksite could be expanded to the field to provide training anytime, anywhere, and to integrate actual experiences into real-world environments. Shin and Dunston (2009) quantifiably demonstrated the benefits of using AR visualisation in guiding steel columns and anchor bolts assembly tasks under experimental scenario. The experiments first used an AR system prototype (ARCam) and conventional method (total station) to guide assembly tasks. They then evaluated the benefits of inspection with ARCam over the total station in terms of the location and alignment precision of steel columns and anchor bolts. The results of the experiments indicated that although the AR approach was less precise (steel columns and anchor bolts usually require accurate placement), it can satisfy standard tolerances, and the simpler and faster setup may compensate for its shortcomings. Finally, Reinhart and Patron (2003) concluded that using AR visualisation in assembly offers advantages wherever there is a large proportion of search time, where workers have to master frequently changing work contents, or where the assembly task is very complex and requires a large amount of information.

2.5. Summary

This chapter reviewed different visualisation means in guiding general assembly tasks. Although VR technology has been widely used in the assembly area as an alternative to traditional drawings or manuals, the record of applications of AR technology in the construction assembly, an advanced version of VR, is almost blank. The promotion of technology is inseparable from the investigation of human cognitive issues that relate to the actual practice of a certain technology. Unfortunately, few research works have actually looked into or addressed these issues, leaving a gap in the application of AR to construction assembly. Therefore, the next chapter sets the cognitive stages for potentially mapping AR technology to specific construction applications, analyses the possible underpinned cognitive theories, and puts forward the theoretical framework, from which the research goal is defined.

CHAPTER 3. THEORETICAL FOUNDATIONS

3.1. Potential Benefits of Using Animated AR Visualisation in Assembly

While the aforementioned studies have made a significant contribution to understanding the product assembly process, several key issues remains unresolved within the assembly domain. For example, researchers have yet to acquire an in-depth understanding of an assembler's cognitive workload when using AR as an alternative to manual procedures and VR. The images of the 'to-be-assembled' objects in VR systems only reflect their bilateral or multilateral positioning, and thus do not take into account the dynamic context (e.g., displacement path and spatial interference). To acquire the information context such as the assembly path and fixation forms of parts/components, assemblers are often required to rely on memory retrieval after being subjected to static augmented cues.

To address this issue, dynamic animation juxtaposed with an AR platform, can be used to enable the assembly process. It is envisaged that a higher degree of integration between information retrieval processes and task operations can be achieved by reconstructing the dynamic animation as real-time guidance in the working area, the main point of focus for the assembler. This is in stark contrast with the manual/drawing system where assembly typically switches between retrieving and interpreting information, selecting the component to be assembled and putting components together. The use of AR enables the 'to-be-assembled' components to be placed at designated work spaces by following both virtual and animated pathways identified from an HMD or on a computer screen (Figure 4). The physical components and their virtual counterparts are able to be 'spatially overlapped' and therefore assemblers are only required to conduct one visual transition, that is, between the selection of those components to be assembled (work-piece stocking area) and the assembly point. Furthermore, since the information context regarding numerous assembly steps necessitates consecutive page placement due to the limited page sizes of 2D drawings/3D manual prints (paper being the typical medium), the difficulty for information orientation is comparatively greater and continual visual transition is almost inevitable. Aside from movements like picking, comparing, grasping, rotating, connecting and fixing the to-be-assembled components, which typically occur where the work-pieces are stocked or assembled, assemblers have to undertake several non-assembly-related kinetic operations to understand the assembly process such as paging up/down, head swiveling and comparing various elevations. An animated AR visualisation is able to pre-define the tasks required (including non-interfered assembly paths) by an assembler so that they can readily follow the process to be considered. It is envisaged that AR can eliminate time consuming searches for information, and bridge the gap between interpretation and memorisation of information and retrieval or recall of that information. AR can create a framework of associations that aid recall and learning. The following sections observe working patterns and AR's capability from the perspective of human cognition, along with the analyses of feasible reasoning borrowing theoretical foundations as cognitive explanations.

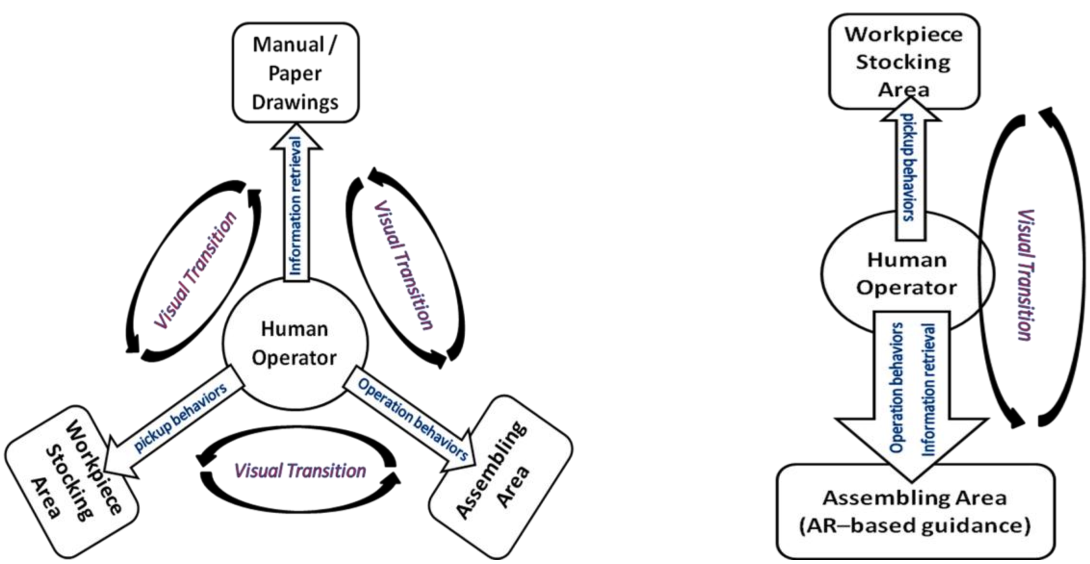


Figure 4. Visual Transition between the Conventional Visualisation Means (2D Drawings/3D Manual Prints) and the Animated AR Visualisation Means

3.1.1. Enhancement of Information Retrieval Capacity

Information retrieval capacity typically differs between individuals since it depends on personal expertise obtained from training or practicing, as well as the difficulty of the assembly task itself. Effective retrieval capacity refers to a series of fast mental behaviours, i.e., searching, analysing and interpreting information. A low level of individual retrieval capacity on the other hand, generally hampers the transition from informational novice to expert. From the perspective of searching for and accessing information, operating information is detached from equipment, tools, and materials, with the exception of control panels and where lighting, frequency of use, and the size of parts allow physical labels or tags to be attached. The worker needs to search some types of medium for information, often in the form of an annotated drawing or manual print. A great deal of time is typically spent on finding and reading procedural and related information. It seems obvious therefore, that accelerating the search for information would benefit task performance. To solve this trade-off, animated AR visualisation can save the worker a time-consuming search by triggering information with little user effort. It provides a more effective method that aids information retrieval compared with conventional assembly guidance, where unilateral information retrieval behaviour is supplanted by the interaction between multimedia and the human.

- The Constitution and Relation of Information Context in Paper-based Visualisation

To accomplish assembly tasks, a series of elevations of components/parts is typically the first class of information that assemblers pay attention to. The information context encapsulates the components' assembly relations and overall structure, which puts forward a high demand for the expression of paper-based visualisation. In addition, the information context in paper drawings involves component specifications and the technical requirements of the final product or segments, e.g., dimension, texture, material, painting, product quality and testing. Each assembly segment is expected to complement the next and coherently fit together to form information for the purpose of guiding the assembly task. More specifically, the information context consists of sub-assembly relations between each to-be-assembled component. Accordingly, it is ultimately matched to the parts, being a dimensional and functional matching between the contacting surface of assembled and to-be-assembled components. For example, since a nut matches a bolt, retrieving the diameter information of a bolt is important to a successful nut and bolt assembly; since concave matches convex, picking the components with the same contacting surfaces typically leads to a successful assembly. Besides this, accumulated experience also contributes to assembly relations determination, e.g., a rigid component usually braces a component of similar rigidity, and one type of colour generally corresponds to another specific colour from an aesthetics viewpoint.

- Retrieval of Information Context Using Animated AR Visualisation

The coherence of information cannot always be guaranteed. Animated AR visualisation provides a dynamic demonstration of consistent information context via animation segments which are displayed with each assembly step. Users can detect the existing dimensions from already-positioned components as well as virtually to-be-assembled components attached by a see-through HMD or projector. At the same time, animation dynamically demonstrates the assembly process in HMD by closely aligning the virtual to-be-assembled objects to the already-positioned ones assembled in the ideal positions. This enables users to mimic each assembly step and lowers the difficulty of the operation. Demonstrating a series of virtual animation segments that seamlessly integrate with the real environment, AR replenishes the perceptive and cognitive vacancy caused by individual differences in information retrieval capacity, and it lowers the certain degree of influence that the task difficulty imposes. Consequently, animated AR visualisation eases information retrieval.

3.1.2. Collaborative Assembly Guidance

Another characteristic feature of animated AR visualisation means is in lending collaborative guidance to the user. Within each assembly step, augmented animation dynamically and sequentially ushers the position changes of spatial components in a way that the user triggers each animation segment. When completing each animation segment, AR turns into a visual tool for presenting the statically augmented images of the component, as well as the attached information. In parallel, this pattern is temporarily suspended for the next triggering by users. At each suspended interval (after the preceding section of guiding animation), users have sufficient time to inspect the installation to date and to process the information for the selection and position of the next component. Through this method, implementing the assembly and retrieving the augmented guidance can be conducted collaboratively and simultaneously. Following this step by step collaboration, the visualisation means is also able to improve the performance of the assembly operations of novice assemblers, proven by Baggett and Ehrenfeucht (1991) via an experiment-based comparison methodology. They selected two groups of participants (inexperienced novice assemblers and experienced assemblers) and applied a training scenario. During training, the inexperienced group viewed a video of each subassembly being put together (with no information regarding the final build), while the experienced group viewed a video of subassemblies being put together in the correct sequence. Following this, a clear interaction between knowledge of the assembly and activity, and the impact of the AR visualisation was identified: for inexperienced novice assemblers the subassemblies plus the sequence representations under AR visualisation led to better post-training performance, while for the experienced assembler there was no difference in the effect of sub-assemblies and sequences. By seeing the assemblies, plus the sequence information being built into the AR visualization, this made it possible for the inexperienced novice assemblers to develop assembly skills after the AR training.

3.1.3. Reduction of Assembly Error

Darius Miller and Swain (1987, 223) revealed that working stress can impair task implementation. They made reporting two findings in their research which showed that novices and experts were equally likely to make mistakes in tasks under low stress, and novices were more likely to err under high stress. They also suggested a feasible explanation, which was that in practice, assemblers would normally study the sub-assembly relations of components (cognitive period) when first exposed to an unfamiliar assembly task. However, when suffered from a scarcity of personal expertise and practical experience, or driven by actual stimuli like working efficiency and required piece rates, a novice might spend considerable time in this phase prior to the assembly itself. In addition they might undergo high mental stress and make mistakes due to possible misunderstandings during the initial phase of information retrieval. Added to this, checking prior mistakes could further exacerbate their mental stress. An effective way to reduce the difficulty in cognition without harming task performance is by making the most important dimensions of the components quite distinct. That is, the virtual components can be selectively rendered to make sure the superfluous dimensions are less distinguishable. The theoretical support to this is derived from the ‘exemplars principle’, which, briefly, is that altering the colour of target objects will not influence performance unless the task requires the encoding of colour (Logan, Taylor and Etherton 1996, 622). Furthermore, as improvements in performance are frequently due to reducing the processing of irrelevant stimuli (Haider and Frensch 1996, 332), important dimensions can be artificially registered in the context of animated AR visualisation while the less important ones are omitted. By shortening the gaps in mental ignorance of retrieval behaviours, task performance improves and assembly errors are likely to be reduced. In summary, animated AR visualisation has the potential to relieve mental stress by supporting the augmentation at a virtual and real interface, lowering the cognitive workload and enabling collaborative guidance.

3.1.4. Stimulation of Motivation

Another noteworthy and characteristic feature of the animated AR technique is that the novelty of the interactive experience in operating AR may stimulate motivation for the task at hand. As Chignell and Waterworth (1997, 1845) stated multimedia can produce a rich sensory experience that not only conveys information but also increases the motivation and interest of its operator or viewer. Animated AR visualisation is a worthwhile multimedia for increasing motivation since it offers a life-like assembly guidance environment and enables interactive operation for users. To enhance this life-like nature, the dimensions of registered virtual components can be manifested attractively through such themes as colour and font, and graphical arrows can be added in, all with the aim of reinforcing the user’s focus and improving the discrimination between surrounding environments. Moreover, environmental elements like lighting and object shadow can also be included as a part of natural environments. Since the improvement of interactivity contributes to motivation in assembly, more advanced developments could be considered for the construction of animated AR visualisation, for instance, adding more types of animation control such as vocal control and artificial intelligence components like assembly interference detection.

3.1.5. Improvement of Spatial Cognition and Reduction in Cognitive Workload

To decrease information-related activities which make demands on the cognitive workload, the relationships of virtual object, spatial location and spatial cognition have attracted considerable attention from researchers. Anderson (2004) discovered that the placement and arrangement of imagery-related spatial objects (positioning and changing the spatial layout of virtually rendered objects) was subject to the user’s proficiency in physical spatial cognition. Repetitive encounters with a particular space or spatial placement resulted in people (usually without any conscious effort) building up an internally enduring representation or ‘cognitive map’ of the space (Thorndyke 1980, sec. 2: Representations of Spatial and Locational Knowledge). Ulrich Neumann and Majoros (1998, 5) also concluded that people preferred to know where information could be found and that the information shown, spatially underpinned the attention of this information patch. As far as attention was concerned, by incorporating virtual objects into real-world scenes, the objects could become the part of that scene and became almost spatially defined entities just as other actual elements did. They have also provided evidences that it is in the nature of human attention to work spatially. Combined with the real context, the cues concerning the property of virtual objects can also be added to the registered objects themselves so that they do not impinge independently on the real context. As for the AR visualisation itself, the virtual 3D components could become the embodiment/counterparts of real components in a real assembly environment. Furthermore, with the feedback of other ‘non-situated’ augmenting elements like recorded voice, animation, replayed video, short tips and arrows, AR can simultaneously guide the user through the entire assembly operation, ease any tension and notify an erroneous assembly, and more significantly, facilitate spatial recognition. In summary, the above discussions lay a theoretical foundation for the assumption that compared with 2D assembly drawings/3D manual prints/VR visualisation, animated AR visualisation is possibly the most effective choice for enhancing spatial cognition and decreasing cognitive workload in guiding product assembly. The functionality of augmentation is in its capability to enable static and dynamic registration of graphically virtual objects and their assembly paths on pre-defined markers in a real environment. With this method, an immersive augmentation interface between reality and virtuality is constructed, enabling the user to conduct real assembly tasks whist observing a series of virtual processes.

3.1.6. Facilitation of Short-term Memory Processing in Human Cognition of Assembly

Ackerman (2007, 236) concluded that an expert assembler typically showed satisfactory ability of information recall and reorganisation from related short-term memories whilst a novice assembler typically performs poorly in this regard, and such capacity might help an expert assembler mentally construct the contents in assembly guidance without spending too much time in mental retrieval. In other words, information novices typically demonstrate a high degree of dependency on their short-term memory. Due to the differences in strategies in memory processing or the capacity to store short-term information, the AR memory that stores previous transient physical information could be differentially retrieved in specific time-step to the assemblers. Therefore, investigating the area of this short-term mechanism in human beings could provide a new horizon for the ergonomic improvement of ongoing task performance. AR could be implemented as an alternative to the conventional means of visualisations in guiding assembly.

3.2. Theoretical Foundations for Supporting the Proposed Benefits

This section presents the relevant theories that are used to justify the proposed benefits in section 3.1. Consideration of the following theories leads to a multi-perspective theoretical foundations for understanding how animated AR visualisation may operate as an interface for assembly guidance and training at the cognitive level. At the same time, AR has properties that can be understood by integrating following theoretical foundations.

3.2.1. Spatial Cognition Theory

Since the visuo-spatial characteristic is at the crux of AR technology, theoretical foundations should firstly be based on classic spatial cognition theory. There are two types of typology in spatial cognition theory. The first typology states three types of visuo-spatial knowledge: 1) procedural knowledge – allows us to get around in a geographical space and the information forms the basis for navigation, 2) declarative knowledge – simple facts about geographic space and the entities within it, and 3) configurational knowledge –knowledge of geographical space that is essentially map-like, though it contains information about relative positions, orientation, distances, and relationships between spatial entities (Golledge 1991, sec. 3: the Structure of Environmental Knowledge; Mark and Freundschuh 1995). The second typology includes three types of visuo-spatial spaces: 1) haptic space – where the visuo-spatial knowledge is based on touching or body movement; 2) pictorial space – where the visuo-spatial knowledge is based on visual context and 3) transperceptual space – where the visuo-spatial knowledge is based on a combination of multiple information sources or experiences synthesised over a period of time (Mark 1993, sec: Transformations Among These Kinds of Geographic Knowledge). Within the first type of typology, animated AR visualisation is likely to be the integration of procedural or configurational knowledge (Shelton and Hedley 2004, 329). It might be procedural due to the fact that AR is capable of enabling entry into a 3D display, and it allows the user to experience it as if standing in or moving around inside a virtual/real world. It may also be configurational due to interaction modalities, where a user holds a 3D model in their hands, and views the entire geographical space from their own viewpoint. AR users may have a better sense of 3D content due to the cognitive pathways through which spatial knowledge is perceived, verified, triangulated and internalised. Based on the second type of typology, animated AR visualisation may encapsulate both haptic and pictorial spaces, where the visuo-spatial knowledge is gained from physical action and visual input respectively. This classic spatial cognition theory indicates that physical action is not only contained in in-situ manipulation, but also closely linked to the first type of visuo-spatial knowledge: procedural knowledge (Mark 1993, sec: Procedural Geographic Knowledge). Essentially, the combination of in-situ manipulation and procedural knowledge could enhance the cognitive experience and transfer of spatial information.

Thus, combining the strong pictorial and haptic visuo-spatial knowledge acquired from interaction and manipulation, animated AR visualisation reveals its compelling advantages in terms of fast and accurate perception and cognition. The traditional procedure for performing a work task may begin with the person directing their attention to work tools or materials. The individual then discriminates, compares, selects, and aligns the appropriate work-piece. Finally, the individual manipulates devices or tools to finish the job. By inserting the required information into the user's real working environment, human abilities can be improved in such tasks as detection of meaningful stimuli and patterns, integration of information, comparison to standards, and qualitative judgment. Here the human working cognitive model of observing the spatial phenomenon could be integrated with the varied forms of pictorial and haptical visuo-spatial knowledge, which is called the synergetic system (Haken and Portugali 1996, 53). Like the mechanism of knowledge acquisition within the synergetic system, AR visualisation might also hold the opportunities through the integration of visual, spatial and sensorimotor feedback. Therefore, it is proposed that AR visualisation works as a powerful spatial visualisation tool for guiding assembly task because of visual and spatial cues set in the context of everyday user surroundings and due to the sensorimotor feedback users receive in response to manipulation inputs combined with visual and spatial cues.

3.2.2. Active Vision Theory

It is commonly accepted that visual perception is the ability to interpret information and physical phenomena from the effects of visible light reaching the eye. Visual perception is typically an active information process which links visual acquisition to acting and moving in the physical world, as stated in the first coined concept of active vision theory by Ballard (1991, 57). The kernel of the active vision theory is that vision is a tool used for sensory exploration of the environment, using an action-involving perception. Clark

(1998) defined that the visual scene, where active vision behavior happens, may be nothing more than a kind of 'subjective illusion' caused by the continuous scanning of small areas using short attention periods. AR visualisation is a platform to sustain the visual perception that links the locomotion of virtual components and the user's visual system. With this link, deriving information about one's environment (physical presence) and the locomotion of components may therefore be paramount in making conscious cognitive assertions, eventually leading to information acquisition or decision making. The nature of the visual image cannot be separated from the action of the object; that iterative processing is governed by visual and motor processes alike. A general feature of cognitive organisation is that units at lower levels of abstraction feed information to other higher levels. However, the levels are not sequentially related, but embedded, each engaging in its own cyclical system with the environment (Shelton and Hedley 2004, 333). The mechanisms for knowledge representation exist inside behavioural processes. A behaviour is a sequence of cognitive events and actions, a set of visual, planning, memory, and reasoning processes working in a cooperative manner and acting on the system itself or its environment (Aloimonos 1993, 18). An adaptable and practical visual system is meaningless without action. Therefore, knowledge acquisition or learning under AR visualisation, underpinned by active vision theory, is more successful because of its inclination toward well-defined behaviours (animation) instead of general purpose representations set only as static representations in conventional visualisation means.

3.2.3. Short-term Memory

The formal concept of working memory (the WM) was coined by George Miller, Galanter and Pribram (1960). It was proven to be a form of 'short-term memory' or 'short-term store' within cognitive psychology, and reflected the capacity of maintenance and recall of short-term memory segments in the human memory. This concept referred to the structure of human memory and the process for temporarily storing and manipulating information such as memory-piece retrieval and expertise recall. To date it seems it is the limit of the individual's capacity for cognition and the strategy difference in short-term storage and retrieval that embodies the different levels of WM capacity. Since the WM mechanism is identified to be very complicated, scientists have carried out a great deal of research to discover the essence of the WM, short-term input and output of representations and the relation between theWM and long-term memory (LTM), (the WM was not proved to be a gateway to LTM) (Richardson 1996, chap. 1: Evolving Concepts of Working Memory). Although the research has greatly widened the psychological and cognitive areas, the mechanism of processing short-term storing is still so far too complex to clarify. However, a consensus has been reached that the WM has both storage and processing functions, and it enables both the temporary maintenance of active representations in memory and the manipulation of those representations in the service of current processing demands. When information is presented, it is firstly retained almost intact for a brief period in the sensory store and then transferred into the short-term store. Content in the short-term store decays very rapidly unless it is kept active through rehearsal or covert repetition of the items read from the sensory store. In assembly work or training, the use of short-term memory is heavily relied upon. For many tasks, accurate performance requires not only that pertinent information be retained in the short-term store, but also that the information be acted on quickly. Therefore the limited capacity of the short-term store has implications for any task or situation in which successful achievement of a task/operation requires the worker to encode and retain information accurately for brief periods of time. To effectively disclose the mechanism of the WM, researchers have developed numerous the WM models based on anatomy or psychology, for example, the anatomy of human and animal brains, anatomical experiments in the functionality investigation of specific parts and psychological experiments on cognitive demands. A review of bypass WM models is helpful to facilitate this research by understanding the mechanism of how the WM functions in information store and retrieval.

- Review of WM Models

The Baddeley and Hitch Model (1974) as shown in Figure 5, is a multi-component WM model comprising two subsystems, a phonological loop, visuo-spatial sketchpad, and a supervisory system, the central executive. The phonological loop stores short-term phonological information (maintains speech-based information) and prevents decay by articulator rehearsal while the visuo-spatial sketchpad stores brief visual and spatial information and prevents decay by visual-spatial rehearsal process. Functioning as an attention controller, the central executive is responsible for directing attention to relevant information, suppressing irrelevant information and inappropriate actions, and for coordinating cognitive processes when more than one task must be done at the same time. The visual-spatial sketchpad can be further divided into visual and spatial components that respectively handle shape, color, texture and loci information. That is to say, the visuo-spatial component of the WM is involved in the visuo-spatial encoding and retention of sequences of loci information, as well as general dynamic transformations of representations within its storage. In this model, each subsystem is in charge of different information resources, and supported by a short-term information storage and rehearsal mechanism respectively.

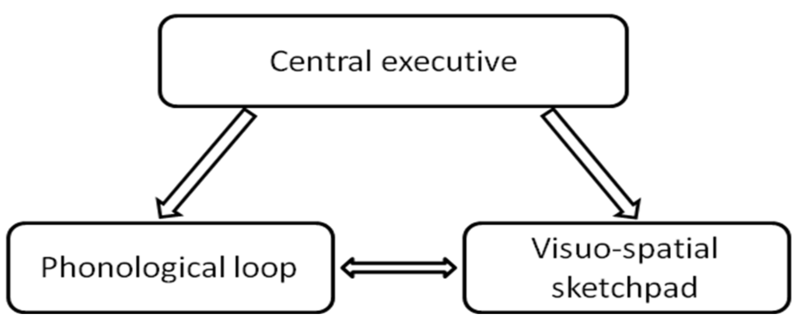


Figure 5. A Tripartite the WM Model by Baddeley and Hitch (1974)

Although the proposal of two newly raised models had their own merits in explaining the relation between the WM and LTM and the retrieving mechanism of LTM, they consciously avoided acknowledging that the WM was a form of short-term memory and failed to take into account certain aspects of the short-term information retrieval issues, such as information input, short-term store, output strategy, visual and auditory information processing differences and so on. In comparison, Baddeley and Hitch's model (1974), for the first time, distinguished the visual cognitive and semantic cognitive functions clearly, as well as relations, coordination, and generic competition for varieties of information under the control of central executive. This model was better able to explain the methods for different categories of information retrieval, information storage (especially short-term store via rehearsal/refreshment mechanism) and retrieval strategies. One of the deficiencies of their model was that it could not explicitly reflect the relations between the WM and LTM. Fortunately, this blank was filled on the basis of Halligan and Marshall's experiment (1991), in which the patients with visual impairment were still able to choose the house that was not on fire, even though they neglected the fire scene of another house. The interpretation could be that although the sensory information did not appear to be available in the WM semantic knowledge was still activated regarding fires and their unpleasant consequences (Bisiach 1993). In other words, as in normal subjects, it would appear that sensory input could gain direct access to information in LTM without going through the WM first. That is why, although being unaware of the reason for decision making owing to the sensory neglect, the patients could still make the right choices. A revised account of the WM mechanism put forward is that it is not working as a gateway between sensory input and LTM (processing information and returning it to LTM), but as a workspace for information interaction and bilateral processing. However, a deficiency in this model is that it is too rough to specify a detailed mechanism concerning how the visuo-spatial sketchpad operates, how the visual representations are stored and how the rehearsal mechanism works. To overcome this deficiency, Logie's WM model (1995) introduced three sub-components into the visuo-spatial sketchpad: inner cache, visual buffer and inner scribe. Meanwhile, the concept of episodic memory was also put forward in Baddeley's learning theory (2000) to further explain the principle of memory recall. That is, if one is to retrieve a specific episode, then he/she must have a means of specifying that episode, and the most likely mechanism would seem to be via the use of context. This learning mechanism is able to raise the potential for AR training. Via providing the consecutive assembly information context (stimuli) in AR scenario, e.g., recorded voice, animation, replayed video, short tips and arrows, links between different contexts and stimuli seem to allow one memorial section to evoke others with more ease, and hence might form a most active and successful areas of recent memory recall span. Should the assembly expertise be engraved and recalled to use by the novice assemblers once and again, they would be closer to the expert assemblers. Here, an improved WM model was constructed for further discussion to further explain the principle of memory recall. That is, if one is to retrieve a specific episode, then one must have a means of specifying that episode, and the most likely mechanism would seem to be via the use of context. This learning mechanism gives rise to the potential for AR training. Firstly the consecutive assembly information context is provided (stimuli) in the AR scenario, such as recorded voice, animation, replayed video, short tips and arrows. The links between different contexts and stimuli seem to allow one memory section to evoke others with more ease, and hence might form a most active and successful area of recent memory recall span. Should the assembly expertise gained be retained and recalled for use by the novice assemblers again and again, they would be closer to the expert assemblers in terms of skill. These observations led to an improved the WM model which was constructed for further discussion. .

In the Advanced Baddeley and Hitch Model (Logie 1995) (shown in Figure 6), the phonological loop is in charge of sub-vocal rehearsal and prevents memory decay by continuously articulating the contents. This process is capable of maintaining the material in the phonological store by a recycling process, and in addition, is able to feed information into the store by a process of sub-vocalisation. Similarly, the visuo-spatial sketchpad is used to construct and manipulate a mental map via the providence of memory agents such as shape, color, texture and location. Such a mechanism might be precisely consistent with the thread of animation AR visualisation mentioned above. That is, vocal tips are effective to stimulate the memory, enable a potential sub-vocalisation to the user and strengthen their memory of assembly expertise gained in assembly tasks. In addition, shape, color, texture and loci information of real and virtual components can be taken as the visuo-spatial stimuli from the real and virtual environment, these seem to be able to be refreshed more easily, and are responsible for involving brief memory-storage and capable of evoking memory links through the augmented feature in the AR animation interface. Once the images are imported into one's visual buffer, they will start to decay rapidly. However, a necessary adoption of the rehearsal mechanism could regenerate the images continually and preserve them from decay in visual buffer. The provision of three extra sub-components of the visuo-spatial sketchpad can conveniently explain the application of spatial images and the maintenance of visual representations. For example, a visual buffer utilised as a visual information entrance is supported by the visual cache and inner scribe, which respectively act as a temporary back-up store for representations (no longer being maintained as conscious mental images, but as visual representations). It is also used in the functionality for the encoding of spatial loci (short-term retention of spatial sequences like Corsi Blocks Task and interaction with dynamic representations within visual buffer like Mental Rotation Tasks).

However, a contradiction according to observations of head-injured patients by Riddoch (1990, 268) revealed that there could be a situation where one system becomes damaged while another remains intact. This seems to be a potential suggestion that the inner scribe, visual cache and visual buffer in human memory systems could be dissociated from each other. Summing up, although in this model there still remains an uncertainty in understanding the visuo-spatial sketchpad, at this stage it is enough to be applied to explain some of the complex cognitive activities. In assembly tasks, different guidance enables the assembly information context to be input into the WM buffer in the form of different streams and it shapes diverse memory representations. When a specific memorial buffer is strengthened and reinforced by constant spatial information input, this buffer might be refreshed and become available in a temporary manipulation during cognitive tasks. When resuming the information retrieval process, the more activated memory sections might first retrieved more easily in the phonological loop or visuo-spatial sketchpad, and be linked together later to output all the items with and in the right sequence. Scrutinised evidence has proven that visuo-spatial processing occurs more easily than phonological processing after stimuli (Cornoldi and Vecchi 2003, 169). This reviewed evidence seems to provide firm grounds for speculation that using animated AR animation as assembly guidance through real-scaled visuo-spatial animation input might make memory representations in the mind easier to retrieve, as reflected in retrieval integrality and the sequence correctness of retrieved items, than other visualisation means. In the next two paragraphs, two theories are formulated on the basis of the theories of our predecessors to further demonstrate the possibilities of why animated AR visualisation might be facilitating short-term retrieval.

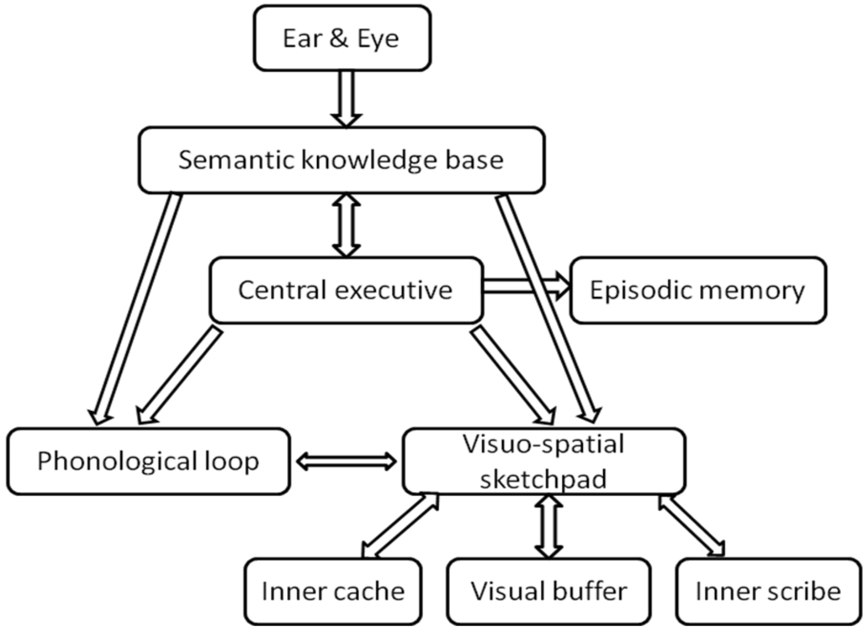


Figure 6. An Advanced Tripartite WM Model by Logie (1995)

- Formulation of Resource and Speed-limited Theory

After the first finding that short-term retrieval in cognitive tasks could be hampered by a considerably high cognitive workload, Rosen and Engle (1997) found that attention-demanding tasks could hinder information retention. Both of the above experiments suggested a positive answer to whether a cognitive workload would differently affect the subjects' the WM capacity. The next question was why cognitive workload caused individual differences in the WM's capacity, and the relationship to performance in numerous tasks of real-world cognition. According to an observation of people's performance in remembering words of different length, Turner and Engle (1989, 140) detected that the differences among people's performance were due to a difference in cognitive resources, as high-span people could use their greater resources to overcome the effect of such a load. An analogous experiment conducted later by Rosen and Engle (1997) also discovered that people defined as having a high or low WM did not differ greatly in terms of automatic strategy in memorising, but differed greatly in terms of the amount of controlled or intentional resources. These fruitful research outcomes brought up the predecessor of resource-limited theory, which first appeared as ‘inhibition resource theory’ (Rosen and Engle 1997, sec: Working Memory Capacity and Retrieval). The concept of this theory is explained as an individual’s retrieval capacity being differently restrained due to the limitations of their mental resources. The explanation of this concept also corresponds with the description of the central executive in the tripartite WM model, whose function is to inhibit distracting events or thoughts that are incompatible with the goals of the current task according to the allocation of mental resource. It is conceivable that the inhibition itself might be a resource-limited process (Neumann, Ewald and DeSchepper 1992, sec: An Act Account of the Stergnberg Paradigm), since irrelevant information gaining access to the WM leaves less ‘mental resources’ for the storage or processing of relevant information.

Based on an investigation into cognition changes in people of different ages, Salthouse (1991, chap. 8: Reduced Processing Resources) found that one of the most influential effects of age on the interpretation of the WM was the difference in the rehearsal speed of memorial representations. This phenomenon is explained such thatcognition changes with age, and is best conceptualised in terms of decreases in the general speed of information rehearsal, with an ‘upper level’ for rehearsal speed which is specific to a particular age group. A derivative theory called ‘resource and speed-limited theory’ was formulated in this research on the basis of the combination of resource-limited theory and speed-limited theory. This was conceived for the purposes of demonstrating the feasibility of using animated AR visualisation to facilitate cognitive tasks from a cognitive science perspective.

In the speed and resource-limited theory, the rehearsal mechanism could prevent decay in the representations of the WM. However, such a rehearsal (refresh) typically occurs at time intervals that need a low cognitive workload or no cognitive workload, and both speed of rehearsal and cognitive rehearsal resources have limits. Even though intervals do not need a cognitive load, the speed of refreshing the retrieved information still depends on the size of those intervals (time). It is envisaged that to learn through animated AR visualisation, more usable cognitive resources could be set aside and utilised by the WM model since the cognitive workload is mostly lowered. People with more cognitive resources would be better able to memorise the relevant information via restraining irrelevant information at intervals. This guarantees the AR user sufficient refreshment intervals when concurrently retrieving the visuo-spatial context (cognitive processing) and conducting assembly (motor processing) based on what they have retrieved from the AR visualisation. The possible outcome should be that the user remembers the previously retrieved context more easily and recognises the particular clue as one that had been previously exhibited in a specific time and place. On the contrary, human rehearsal might be suppressed when short-term representation is not refreshed enough for concurrent motor tasks, since drawings or manual guidance might place more of a cognitive burden on the user, and some forgetfulness may occur. Since there is also a limited pool for human cognitive resources to actively represent memory sections; people may have better performance in processing cognitive retrieval tasks that require less cognitive workload.

- Formation of Retrieval Competition Theory

The formulation of retrieval competition theory originates from Hasher and Zacks (1988, 193), who confirmed that it was not the size of human memory that determined performance but how well the content of the WM can set the goal. This means that human performance could be effective if the retrieved representations are closely tied to the goals of the ongoing task. This explanation refers to a mechanism that inhibits the irrelevant retrieval of memories (a competition between irrelevant and relevant material at the time of encoding). If the inhibitory mechanism is poor, the ultimate consequence of information retrieval would be an increase in irrelevant or marginally relevant ideas in the WM, thus dividing attention and producing interference. The inhibitory mechanism serves to restrict the WM in accessing the information relevant to the task being carried out at the time. Because the WM was limited in terms of the amount of information that could be held, there was less task-relevant information available when the competition between relevant and irrelevant retrieval was more intensive. Aside from this, competition could also slow down immediate retrieval during a memory search. A typical case is that of giving a speech, during which a presenter should try to maintain content coherence by suppressing the improvisational retrieval of non-speech relative materials. The inhibition of improvisational interference in this example is regarded as the practical reflection of retrieval competition theory.

When remembering a list of seven words in order, one should start with recalling the first word, the second word and then any following words which are closely related to the preceding words (Baddeley 2000). Errors in serial recall tasks are often confusions of neighbouring items on a memory list, showing that retrieval competition plays a role in limiting our capacity of sequential retrieval tasks such as assembly tasks. In traditional assembly visualisation, the static context of assembly drawings/manuals cannot be coherent in visual presentations, as they are only a battery of static planar images for linking memory chains and representations. The retrieval of a specific plot of information context may be blocked by the randomly increased activation of other different plots. Based on the formulated retrieval competition theory, the key to successful processing might be to suppress the irrelevant information from the WM, by only allowing the relevant information to enter the WM. The best option is considered to be the introduction of relevance emphasis, which is the omission of irrelevant representations of the assembly context either entering the eye or becoming semantic knowledge. The scenario of designing an animated AR visualisation should be technically flexible to control the relevance or irrelevance of the assembly context. Another issue concerns how the relevant representations could form a complete memory chain. Here, a concept called ‘connectionism’ (a mechanism of forming association) is aided to explain this (Baddeley 2000). The amount of short-term memory communication among a series of representations depends on the ‘strength’ of the connection, and the level of activation of one representation is determined by all the activations. This impact on memory that one representation has on another depends on the extent of its own activation level along with the strength of the connection between the two representations. As a result of this simple mechanism, specific activation over a series of representational memories can give rise to a pattern of activation of another representational memory. If each of these patterns of activation can be regarded as signifying one representation, then the production of this representation can lead to the retrieval of another. Through animated AR visualisation, when each augmented step of assembly becomes represented in the next one, memory activation might be spread through the connection until the whole memory chain is established. This way, it is envisaged that an association will form to temper the competition effect and increase the performance of short-term recall.

- Spatial Cognition Contributions to the WM

Spatial cognition is typically associated with the comprehension of geometric properties such as distance and size, as well as physical properties such as colour, texture and mass. This gives rise to the supposition that the content of an object (for example, its text expression or its shape) can be associated with its features as a 'work' object. AR visualisation, where visual patterns are able to be processed in terms of edges, contours, grain and patterns of light and shade, might create a framework of associations that aid recall and learning; these are termed spatially augmented stimuli (for example, an array of callouts and attached parameters in a work-piece scene). These stimuli together may form a framework when subjects use a classic mnemonic technique, the method of loci, to remember a list of items (Neumann, Ulrich and Majoros 1998, 7). Each association of a virtual object with a work-piece feature is a basis for the linking of 'memory pieces' in the human memory. With the loci method, a subject could better associate to-be-remembered items according to the artificial hints or landmarks on an imaginary path. When starting the recall process the subject 'mentally walks' onto the path. As he or she encounters the artificial hints or landmarks, the item associated with the landmark also appears, and it is therefore available to the WM. In addition, adding these detected and augmented stimuli, every exposure to a stimulus could lead to an internalised trace of that stimulus, which is called the exemplar or instance-based model (Logan, Taylor and Etherton 1996, 636). Using these exemplars or instance-based models, information recall capacity could be strengthened post-performance, and task performance could be improved since more relevant instances are likely to be retrieved. Using an augmentation interface to conduct assembly guidance under AR conditions, the real and virtual components can be 'hand-held', while the assembly paths, sequences and fitting relations can also be 'shown in hand'. In the real assembly task, these elements might be triggered as by-products of the enhanced work-piece scenes and are more subject to the visuo-spatial sketchpad.

Compared to AR, drawings or manuals are apt to be confused with real distractors such as irrelevant or unattended environmental, or visually presented items such as pictures or patches of color or confusion can occur with concurrent spatial processing. According to a review that the relevant stimuli of a task could trigger access to the visuo-spatial memory and strengthen the storage and maintenance of task-relevant information (Toms, Morris and Ward 1993, 682), it is concluded that these irrelevant distractors could suppress the ability to memorise assembly procedures and could impair subsequent information retrieval. This could also be explained using Baddely and Hitch's tripartite WM model. Irrelevant speech effect such as noise could prevent the circulation of phonological loop (Salame and Baddeley 1982, 155) and irrelevant visually presented items could also prevent the reorganisation of items in the visuo-spatial sketchpad (Logie 1986, 238). Finally, according to Logie's theory (1995), a system (visual-spatial sketchpad) that incorporates an 'inner cache' and 'inner scribe' possibly supports the visual WM (since 'inner cache and scribe' have direct links with the processes that underlie visual perception and enable visual materials to be maintained by a form of visual rehearsal respectively). Visual-spatial perception in AR visualisation might be embodied by the visual virtual images of the to-be-assembled objects while the visual rehearsal might be processed by step-by-step assembly operations of real components. Therefore, visuo-spatial assembly representations might be relative to their materialised real components. When engaged in this, users' short-term memory might be strengthened through the visuo-spatial cognition mechanism.

A compelling experiment conducted by Psotka and Pflaging (1995) compared the recall efficiency regarding 21 familiar items (such a potted plant, a ladder). The experiment applied and compared two visualisation means of presenting 21 familiar items, VR and AR, where VR was the comparing benchmark. In the VR state, items were programmed to appear as though they were arranged in a circle, and the subjects swivelled in chairs to observe them. In the AR mode, items were arranged as in the VR condition, but appeared as though they were projected onto walls. After viewing, the subjects under AR conditions recalled as many items as possible in any order. The result of this experiment revealed that in the VR environment, the items were too disassociated from the real environment to form effective recall that could be strengthened by spatial cognition. However in the AR state, the items were akin to a real-world setting and they were tightly interrelated with one other and the ambient environment. The testers who recalled as many items as possible in any order found it easier to mentally reconstruct the spatial layout in the recall process owing to the improved relevance of the 21 items in the AR format. Therefore, the competition effect was suppressed to some extent.

3.3. Proposed Theoretical Framework for Validation

This section raises the theoretical framework of this research, as depicted in Figure 7. In the context of spatial cognition theory, active vision theory and WM theory, this framework summarises existing mechanisms concerning visuo-spatial information processing and WM processing. The setup of this theoretical framework aims at validating the invalidated aspects of spatial cognition theory, active vision theory and

WM theory when transferring from the psychological arena to practical instances. It is noticed that this framework leaves out the phonological components of the WM model which handle the sub-vocal rehearsal and the articulation and restoration of LTM related information mechanisms. Therefore, in parallel with the framework setup, the theoretical contribution of this research will be the 'theoretical exploration' from the framework that refers to the processing of the WM and the relevant mechanisms. The following paragraph elaborates on how this framework integrates existing findings as well as the unconfirmed aspects of theories that correspond closely with construction assembly information processing.

In a typical construction assembly, the particular assembly information context is retrieved as the input flow and retained as a short-term memory representation in the central executive. This is the very beginning of the physical layer of processing visuo-spatial short-term information, enabling different forms of visualisations to enter the central executive of assembly operators such as shape, contour, color, texture, location and size. Given the different types of assembly visualisation means (2D drawings, 3D manual prints and animated AR visualisation), the information flow of the assembly information context can be roughly divided into 2D planar information, 3D planar sequential information and 3D spatially augmented sequential information. Once different forms of information flow into the central executive, they are taken over by the visuo-spatial sketchpad and then the visual buffer, the working mechanism of which has been elaborated in the improved tripartite WM model raised by Logie (1995). At the same time the inner cache begins to uptake the information, stores it and then interacts with the visual buffer in terms of temporary 'backing up' and 'reverse outputting'. Decay or forgetfulness then occurs differentially between individuals until the short-term representations are rehearsed or output, causing varied rehearsal or recall effects in the form of information integrity and sequential correctness. This described cycle of short-term visuo-spatial information processing generally remains at the physical layer of the framework, having been confirmed by the purely psychological research work.

Underpinned by the human cognitive theory of pure psychology, the argument that variables such as: the amount of mental resources, rehearsal competition, rehearsal intervals and rehearsal speed, act on individual disparities in rehearsal or recall effect (integrity, sequential correctness and learning curve), has reached a general consensus. For example, for average cognition-demanding tasks, the less the mental resource is saved, the lower the integrity or sequential correctness of recalled representation. Conversely, inhibited rehearsal competition contributes to higher integrity, more sequential correctness, or an even faster learning curve. However, such an argument is not capable of providing a persuasive explanation of the specific issues that are involved in field assembly tasks in the construction arena, since previous theories have not experimentally validated their applicability when transferring from the psychological arena to practical instances. A series of unknown issues exist from the theoretical perspective: can spatially augmented visualisation assembly guidance, combined with sequential context, save more cognitive resources or effectively inhibit rehearsal competition more so than other visualisation techniques? If certain visualisation technology in assembly guidance/training can better stimulate the on-task performance or cater to the recall and learning effect of training, how does it impact on cognitive endeavours? Can it set aside more resources or effectively inhibit the rehearsal competition? Does the possible underlying rationale include the enhanced work-piece scene, introduced relevant emphasis, lowered memorial searching or formed memorial association?

Notwithstanding this, the limited research works available has not clearly accounted for the mechanisms of how the different visualisation means of guiding field assembly tasks exert influence on rehearsal intervals, rehearsal speeds in short-term memorising, and further memorial integrity and correctness. This current paper will not fully consider these aspects due to:

1. *Applicability:* The methodology of validating the effects of rehearsal intervals and rehearsal speeds on memorial integrity and correctness is typically derived from psycho-

physiological measurements within the psycho-psychological arena, for example, heart-rate variability and eye pupil-response. How to conduct it externally is not the objective of this research.

2. *Difficulty of developing new measurements*: Because these two factors are closely related to cognitive science or psychology, redeveloping highly reliable and quantitative measurement methods can be quite difficult. In addition these aspects do not align with the current research objectives.

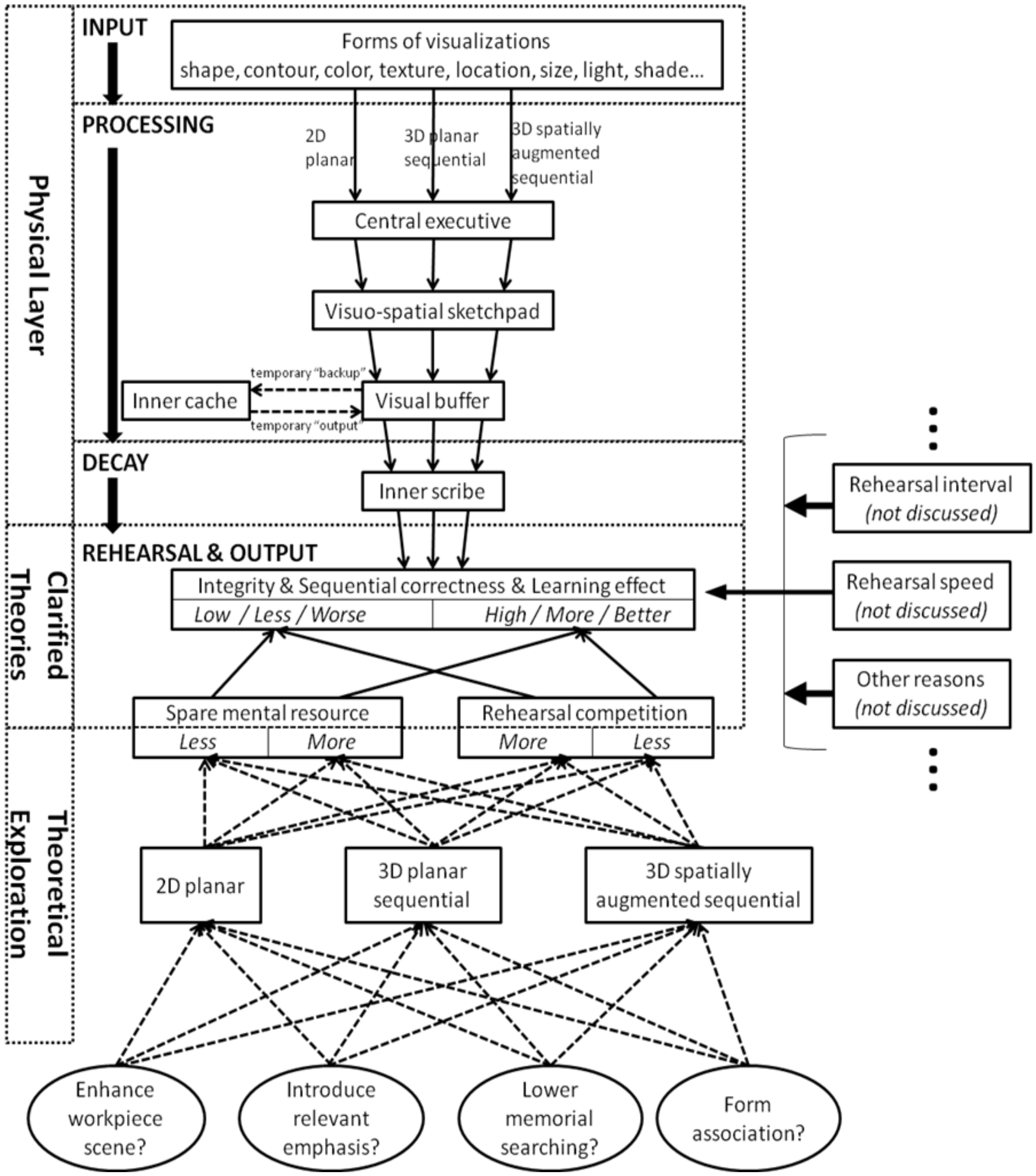


Figure 7. Hypothesized Theoretical Framework for Theoretical Exploration (as given in Dotted Lines)

3.4. Assembly Information Processing Model

In this section, an information-processing model of assembly task is proposed, providing a direct description of the linking of information-related activities and work-piece-related activities. Thus, this established information processing model can aid the understanding of the theoretical framework by organising the perceptual information, the cognitive feedback and the internal psychological visuo-spatial components. The information flow for particular construction assembly tasks within the model can assist in identifying the mental operations that take place in the processing of various types of information from input to output. The information-processing approach provides a basis for analysing the task components in terms of their demands on perceptual, cognitive, and motor processes. The establishment of animated AR visualisation must be in line with the formation of the information processing model, which emphasises the impact of differing visualisations means on the sparing of mental resources and the inhibition of rehearsal competition.

To illustrate how this model complements the contemplation of an AR system, a simplified process of construction piping assembly can be captured by the conceptualised assembly information processing model in Figure 8. In a typical piping assembly task, the worker typically must first lay out the work and decide on the first component (for example, A is the first pipe) to assemble (or a selected starting point if just beginning). Then the worker must identify the to-be-assembled component B with reference to the guidance means. All of these tasks are perception-demanding. After confirming the to-be-assembled pipe B and its target position which is decided by A, the worker then needs to decide how to physically move B to A. The cognitive tasks begin involving the deeper mental work of estimating the first trial position and comparing the results with the target position, i.e., making adjustments. Finally, the worker adjusts the position and then connects the pipes together in right position until A and B are aligned. Following this path, more pipes will be added to the previous piping structure. The cycle of identifying, inspecting, measuring, locating, estimating, comparing, aligning, and connecting is repeated again and again. AR can help the worker to identify exactly the to-be-positioned components by showing the features of a virtual pipe, such as length and diameter. It can also show precisely, the virtual version of the next to-be-assembled pipe in the target position, adjoined to previous ones. Therefore the final layout is displayed in the real view of the worker, which can augment the performance of position estimating and comparison. Since construction assembly is highly repetitive work, the more cycles, the more time saving benefits might be shown by AR visualisation. This model distinguishes tasks between perceptual tasks and cognitive tasks that make up the composite task, and thus it is possible to explain the 'theoretical exploration' part in a theoretical framework. The amount of mental resources to be set aside, and to what extent the rehearsal competition is inhibited, usually depends on the workload of conducting cognitive activities, a higher level of information processing. The emphasis in this research focused on investigating how the performance of cognitive behaviours can better reveal the spirit of cognitive factors such as rehearsal competition and rehearsal resources. Combined with real-time task observation, qualitative and quantitative measurements, the examiner may indirectly recognise the mechanisms concerning visuo-spatial information processing and WM processing that are reflected in physical task performance, which in turn helps explore the to-be-validated aspects of spatial cognition theory, active vision theory and the WM theory when transferring from the psychological arena to practical instances.

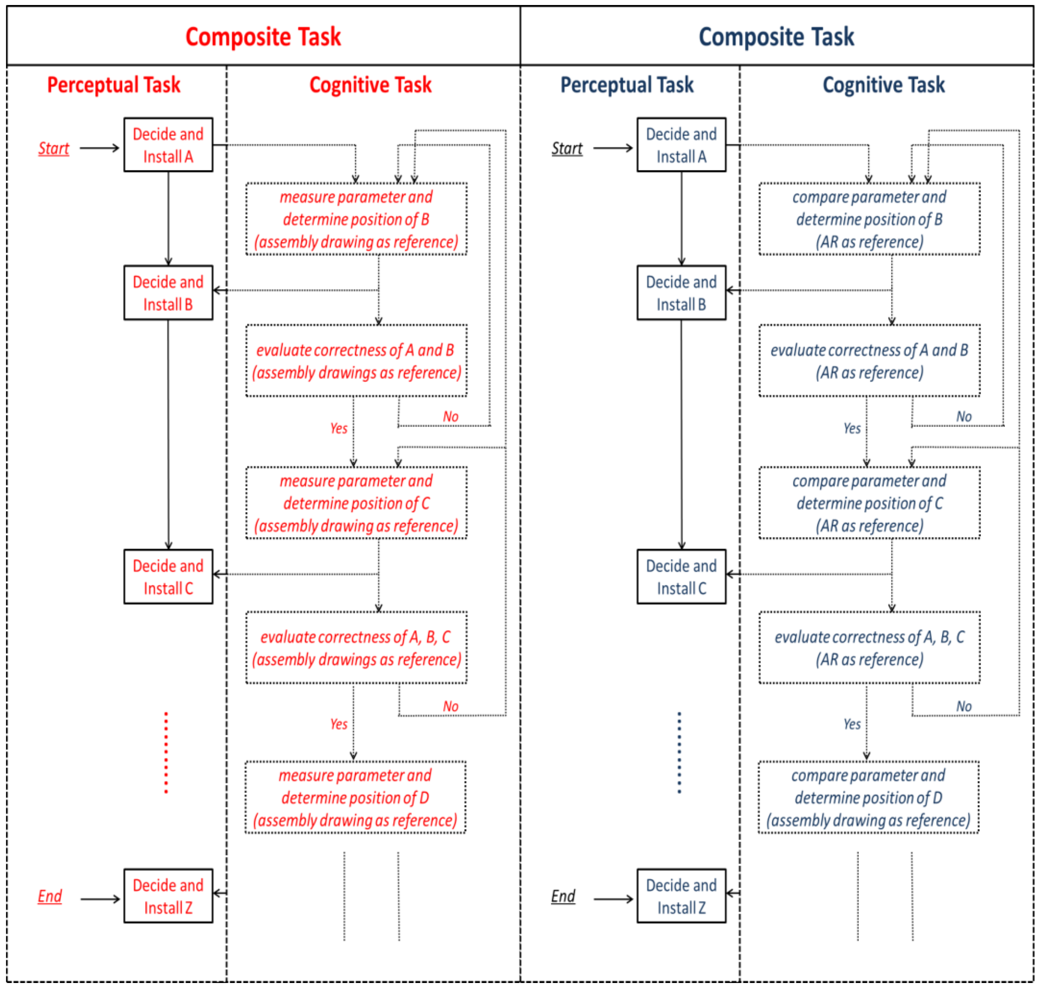


Figure 8. Conceptualised Assembly Information Processing Model under Two Patterns: Left Indicates 2D Drawing and Right Indicates the Animated AR Visualisation

3.5. Summary

This chapter has raised the theoretical aspects for this research to validate. Based on human cognitive theories, the animated AR visualisation presents the possible cognitive facilitation fitting certain parts of the theories. A theoretical framework has been established, which summarises the existing mechanisms concerning visuo-spatial information processing and WM processing in the context of spatial cognition theory, active vision theory and WM theory. The setup of this theoretical framework aims at validating the to-be-validated aspects of visuo-spatial information processing and WM processing, when transferring from the psychological arena to practical instances. The assembly information processing model is established for comprehending the theoretical framework, by organising the perceptual information, the cognitive feedback and the internal psychological visuo-spatial components.

CHAPTER 4. RESEARCH QUESTIONS AND HYPOTHESES

4.1. Research Questions

There are two research questions presented in this research:

Question One (Q1): What advantages can animated AR visualisation provide to assemblers in terms of task performance and cognitive workload, compared with 2D drawings/3D manual prints?

Question Two (Q2): Could the training of assemblers in animated AR visualisation contribute to a faster performance improvement, compared with training with 3D manual prints? Does gender make a difference to the comparative results of the two training schemes? If so, what are the possible reasons?

4.2. Hypotheses

The objective of this research is to examine cognitive potential by revealing what specific facilitations animated AR systems could lend to assemblers, and to provide evidence as to the likelihood of shortening the learning curve of novice assemblers, when implementing the actual assembly or training. Based on this, the following hypotheses are formulated:

Hypothesis One (H1): When compared to conventional 2D drawings/3D manual prints, the animated AR system is able to lower an assembler's cognitive workload in designated assembly tasks, due to the enhanced work-piece scene (mental resources are saved).

This hypothesis was formulated on the basis of the cognitive potential listed above. The reason for choosing the designated assembly tasks can be found in the assembly tasks analysis section herein. In traditional assembly tasks, the cognitive workload typically derives from the field measurements of component sizes by following the dimensional instructions or labels on paper-based assembly drawings/manual prints. The user needs to measure the actual length of the components and select the appropriate one, based on the results of the measurements. With animated AR visualisation, users are able to determine component selection and installation through augmented images, as well as the ambient environment (captured by camera) shown in the display device, rather than conventional field measurement and understanding. Assemblers must compare the length of the to-be-assembled component images with the actual length of real components, within the camera view, and then decide which component to choose and how to install it.

Another pertinent issue is the evaluation of the physical effectiveness (facilitation) of using animated AR visualisation as an alternative to paper drawings/manuals in assembly tasks (the conventional visualisation means is regarded as the comparison benchmark). Hence, the second research assumption is posited in terms of the physical facilitations of applying animated AR visualisation.

Hypothesis Two (H2): When compared to conventional 2D drawings/3D manual prints, the animated AR system shortens the time spent on component selection and assembly operation, and reduces the amount of assembly errors.

If the animated AR system could lend credence to dimension comparison and position determination, the time of component selection and assembly can be significantly shortened and assembly error can be effectively decreased. To validate this hypothesis, concurrent tasks were applied as a technique to compete for human cognition; the rationale is presented in the experiment section. To detail the data collection and analysis, the time spent on component selection and assembly processes was further broken down to searching time plus dimension determination time, and guidance comprehension time plus operation-related time respectively. Likewise, the amount of error was subdivided into three classes: dimension determination error, installation error and afterward error (the discrepancies between assembly guidance and the completed product version) respectively.

Hypothesis Three (H3): Using the animated AR system as a training tool shortens the learning curve of trainees in cognition-demanding assembly. This is based on a sub-hypothesis that training within an AR environment facilitates longer WM capacity, when compared to training with 3D manual prints.

Referring to the discussion of a framework of association, elaborated upon in the 'spatial cognition contribution to the WM' section, the WM usually includes certain mechanisms for forming memory associations (chains) between representations. The formation of memory association is a process of linking the representations that have been previously retrieved. In other words, the memory associations relate to the quality of memorising, particularly for high cognition-demanding tasks. For the purpose of forming the sequential representations, and alleviating the retrieval competition effects (refer to 'formation of retrieval competition theory'), animated AR visualisation presents augmented visuo-spatial contents step-by-step, which is easier to access by the user for memory-clues. As a comparison, paper manuals may not be conducive in the cultivation of end-to-start memory representations. The validation of this hypothesis could uncover an underlying mechanism, by the cognitive alteration of ongoing tasks. Let us assume a formulation of resources and speed-limited theory which lowers the cognitive workload and sets aside more usable cognitive resources that are subject to the WM. It is then posited that lowering the cognitive workload, via the enhancement of spatial cognition, may influence the mechanism of short-term memory retrieval, other than merely easing the ongoing task. With more cognitive resources being set aside, more numerous and longer rehearsal intervals in the retrieval process could be triggered. When using 3D manual prints as comparison benchmark, such a rehearsal might be more suppressed, since short-term representations might not be refreshed enough in the memory and could be forgotten. There is a limited pool of active cognitive resources available for short-term memory representation for every person. The user should show a better performance in processing cognitive retrieval in post-training tasks, i.e., completion time is shortened, proficiency is improved and error rates are decreased. A worthy question regarding post-training tasks is: What are the performance disparities between trainees, after AR training and text manual training? If WM is a factor, the assembler's task performance should reflect a certain level of difference after the two means of assembly training. This would at the very least be from the performance that is related to memorising, for instance, human behaviour corresponding to the recollection of a component assembly sequence and method.

CHAPTER 5. METHODOLOGY

5.1. Introduction

This section includes an overview of methodology, including discussion of human ethics, experimental design, assembly task analysis, prototyping technique and data collection and analysis strategies. From a research perspective, experimental results regarding human cognition in the AR-based assembly process could provide a contribution in establishing principles of successful implementation of AR-based visualisation techniques in the real assembly domain. Before executing the experiments, an analysis was conducted as to which assembly tasks fitted this research, and how to prototype the animated AR system, together with different assembly tasks. Since this research involved human subjects, the human ethics was applied for assessment and approved from the relevant committee of university. Human subjects that were between 22 to 33 years old and comprised of full-time and part-time research students were invited to participate in and perform assembly tasks and assembly training in experimental conditions, under the guidance of a previously constituted sampling procedure. The reason of selecting the non-professional assemblers as the experimental sample was because the research questions and hypotheses of this thesis were restricted in the performance study and the learning and training issues of the novice assemblers (learners), rather than the expert assemblers or veteran assemblers that were from real construction field. The age range of the research students was set as 11 years, which included the young adults and the mature adults. In practice, there are a large percentage of construction assemblers who were in between this age range, therefore, the age range, to some degree, reflected the actual situation in construction industry. Meanwhile, there were both male and female subjects, which met the purpose of using AR visualization to guide and train a wide range of people.

For the implementation of the experiment, the participants' performances were measured by subjective matrices, such as NASA task load indexes and questionnaires, as well as objective matrices, such as task performance observation and time recording. Furthermore, special useability questionnaires and associated data collection strategies like interviews and observations were developed in order to assess the participatory process and certain features of the AR space. Finally, a statistical model was also developed to arrange experimental sessions and collect data. A statistical analysis tool (SAS) was used to test inter-factor correlations for reliable results.

5.2. Discussion of Human Ethics

The human ethics application was submitted to the human ethics committee in the University of New South Wales (UNSW) (before transferring to Curtin University, I was studying in UNSW) and subject to the National Statement on Ethical Conduct in Human Research. There are two methods by which research projects involving human participants are reviewed at UNSW. The first is by the Human Research Ethics Committee (HREC), which reviews all projects containing significant ethical concerns. The second is by one of nine discipline-based Human Research Ethics Advisory Panels (HREAP) which are concerned with research which has minimal ethical impact (Table 1). Panels can give approval for one year only, and in exceptional circumstances, may approve a one-year extension. Since this research did not include vulnerable subject groups or sensitive topics (was considered as minimal ethical impact without a significant risk of harm), it applied to the HREAP.

Table 1. Examples of Minimal Ethical Impact (UNSW webpage: https://research.unsw.edu.au/minimal-ethical-impact)

Examples of "minimal ethical impact" research	**Comment**
Studies which do not involve an intervention that could result in significant harm to participants	*Potential harms may include physical (e.g. insertion of needles), psychological (e.g. emotional distress), and social effects (e.g. cultural sensitivities). If any of these possibilities are likely the application should be made to the HREC.*
Studies which do not involve subjects who are vulnerable	*Studies involving subjects who have a reduced capacity for fully informed consent (e.g. children), those in dependent relationships (e.g. students), and those with diminished autonomy (e.g. prisoners) should generally be referred to the HREC.*
Social science questionnaires on non-controversial, non-personal issues	*Examples of suitable projects for application to the HREA panels are marketing research questionnaires and general surveys that only require basic demographic data. In all instances, respondents would not be identified.*
Observational studies in public situations which focus on non-sensitive areas	*Studies of public behaviour (e.g. use of street furniture, behavioural reactions to art installations, shoppers' behaviour, etc.) may be considered minimal ethical impact. If these observations were to be video-recorded or photographed, HREC approval may be needed.*
Studies of existing de-identified data, documents, records, pathological or diagnostic specimens	*Studies based on historical archives and records, museum specimens, cultural/ historical data placed in public trust and internet sites would generally be considered as minimal ethical impact.*
Collection of certain biological specimens, including hair, nail clippings or saliva	*An example of a minimal impact study might be collection of de-identified hair sweepings from a hairdresser's floor for purposes of determining lead levels in the community. By contrast, a study which involves collection of prisoners' hair for the purpose of determining DNA characteristics should be referred to the HREC.*

The application of the human ethics was submitted on 11 May 2011, to the HREAP, Faculty of the Built Environment, UNSW, and was assessed on 16 May 2011.

In support of my application, I had attached the compulsory documents (Appendix A and B) and the additional documents (Appendix C, D, E, F, K and L). The assessment decision was “Recommended for Approval” (Appendix A with Decision Codes:2b 13a 12c 5a 2a 15b). Meanwhile, the ethics advisory panel proposed three review comments, which I had justified in time (Appendix G). The approval of ethics was valid for one year since 16 May 2011, during which I had completed the entire experimentation.

5.3. Experimental Design

An experimental design regarding the use of animated AR systems in influencing cognitive issues in the assembly process was evaluated. This experimental design investigated whether users, especially novice assemblers could be positively influenced by AR technology. Moreover, the research examines the factors hindering this facilitation. The research design assists with the identification of training effects using AR and assembly manual/drawings, as well as the relationship between the WM and learning curves. The experimental design consists of three distinct phases: 1) mental rotation; 2) main experiments; and 3) useability evaluation of the animated AR system (Figure 9).

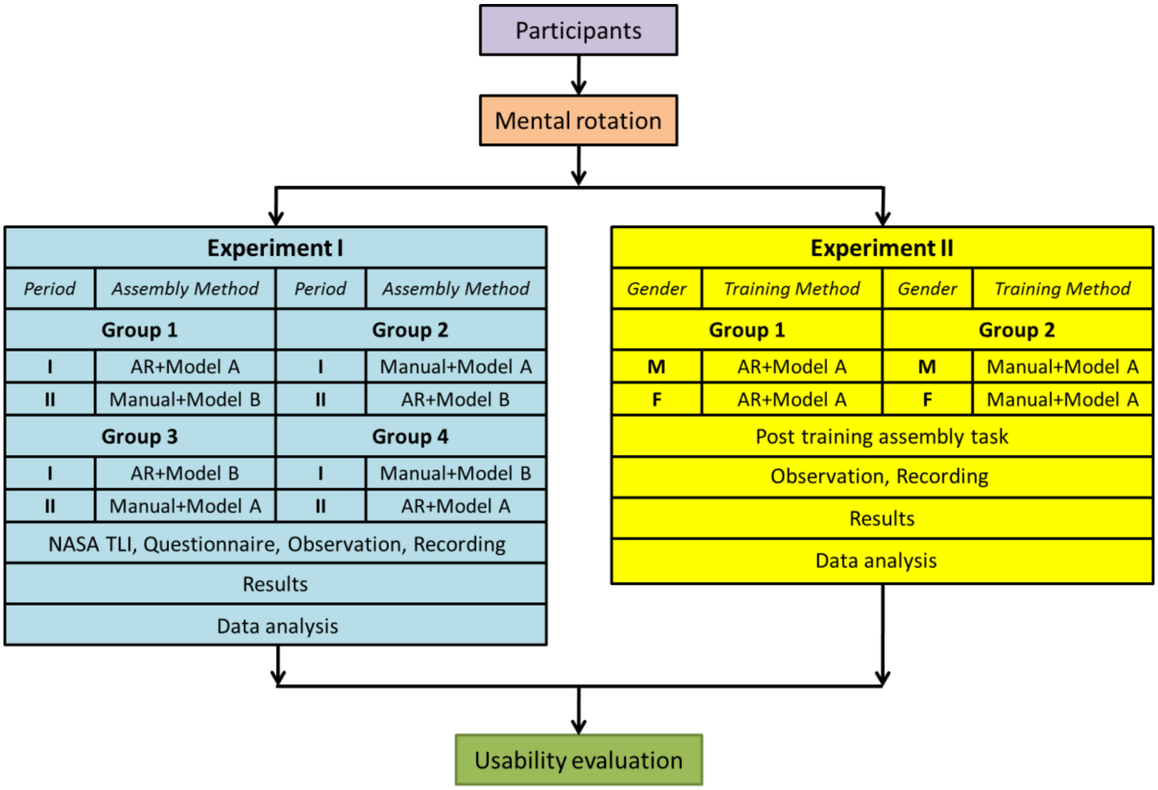


Figure 9. Experimental Design Evaluating Cognitive Issues of Animated AR Visualisation and Conventional Manner in Product Assembly Tasks

Mental rotations were first undertaken to examine spatial-cognitive capacity. Two types of three formal experiments were then executed to compare three scenarios: 2D drawings, 3D manual prints and AR visualisation. The objective of experiment I was to study the nature of cognition on a person’s performance when merging digital virtual information (e.g., AR animation guidance) in a real assembly workspace compared with merging physical information (e.g., guidance manual) in a real assembly workspace. The objective of experiment II was to compare the learning curves of AR training with assembly manual training.

5.4. Pre-task – Prejudgment of Cognitive Capacity

The pre-task of mental rotation was undertaken prior to the main experiments. Its role was to examine each subject's levels of inherent spatial-cognitive capacity. As the former research recognised a relation between cognitive load and corresponding task performance, and the possible influence of cognitive capacity on task performance (Pillay 1994), lessening the disparity of cognitive capacity could lend credibility to the experimental results. The notion of cognitive capacity is a person's ability to mentally move into a spatial space, navigate this environment and manipulate the visuo-spatial imagery. To date, mental rotation is regarded as a direct and convenient measurement of the human capacity for spatial object cognition, far beyond its limitations of merely discovering neurological issues (Zacks 2008). Testers are required to recognise those objects as mental images and rotate them mentally; they then should decide whether one version of the object image is a reflected version of the other (Figure 10). In view of the fact that the task process refers to visuo-spatial input, mental manipulation and visuo-spatial output, (processes that need considerable spatial capacity and cognitive workload), it is secure and reliable to use mental rotation to roughly divide different levels of cognition Kosslyn (1996). The fore-task of mental rotation quiz used the 15 testing items based on a testing sheet. The total achievable score of the mental rotation quiz was 15, indicating that each item represented 1 point. Human subjects were allocated 5 minutes to accomplish the test. Five minutes was set as the average time for people to conduct the mental process of rotating. Based on the author's pilot study, (20 testers) where the average score was 11.4 and 19 testers (95%) scored between 8 and 14 points, it is concluded that a person who scores lower than 8 might have some degree of cognitive disability. Therefore, in formal testing where participants scored lower than 8, these points were not considered appropriate for the experiments.

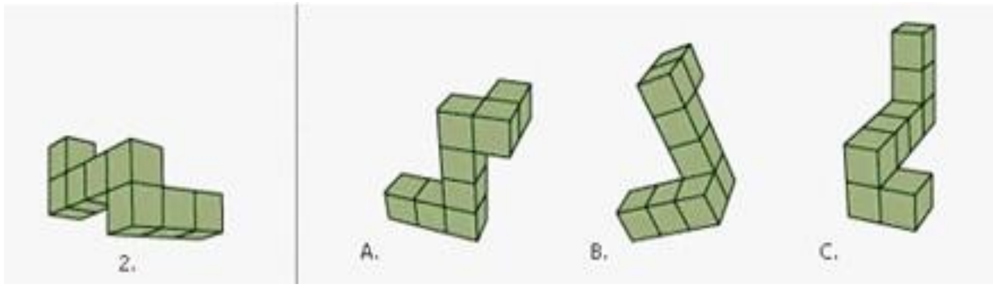


Figure 10. An Example of a Mental Rotation Test Sheet: B is Congruent with the Left Given Object

5.5. Experiment I – Performance and Cognitive Workload

The objective of experiment I was to study a human subject's performance and cognitive workload when merging digital virtual information (e.g., AR animation guidance) in a real assembly workspace as compared to merging physical information (e.g., guidance manual/drawings) in the real assembly workspace. A concurrent task strategy (also known as secondary task strategy) was applied, as it reflected the level of cognitive load imposed by a primary task (Dunlosky and Kane 2006, 1228). The concurrent task entailed simple activities that required sustained attention, such as detecting a visual or auditory signal; typical performance variables being such factors as reaction time, accuracy, and error rate (Rubinstein 2007, 330). Specifically, the measurement should contain mental load (an indication of the expected cognitive demands), mental effort (a cognitive capacity that is actually allocated to accommodate the demands imposed by the task) and recorded performance (an indication of the learner's achievements, e.g., number of errors, time consumption, etc.). Adding a concurrent task, which is also cognition-demanding, the susceptibility of human mental and motor performances could be easily examined. This is based on the tentative hypothesis by Rose el al. (2000, 494) that if the assembly task performances under the two scenarios differ in participants' associated cognitive load, their mental and motor performance would be differentially influenced by the introduction of concurrent cognitive tasks. The actual interference effect that one task imposes on another happens in such a situation that two tasks co-relate with each other in terms of task processing mechanisms. Two key factors which may affect the concurrent tasks are task similarity and task mode (Eysenck and Keane 2005).

Considering that assembling under each means of guidance includes different cognitive needs, devising a secondary task which requires a certain level of cognitive workload may disturb performance of the priori task, at least in the cognitive aspect. Meanwhile, physical performance in cognition-related tasks partially depends on mental processes. When conducting mental processes, a specific portion of human mental resources would be occupied by certain cognitive needs. These are therefore more susceptible if the secondary task is also a task that puts forward a high demand on mentally processing the useable mental resources. In view of the fact that the visual-imagery processing (information retrieval from guidance) and the processing of retention of visually or acoustically presented information share cognitive resource, a secondary task was added to the main task, which required memory retention of visually presented items.

The research measurement of cognitive workload was proven to be diverse. The main measurements of cognitive workload included subjective analytical methods and empirical methods. These included subjective data collection and analysis (usually involving a questionnaire comprising one or multiple semantic differential scales, where the participant can indicate the experienced level of cognitive load), and a ratings scale technique (based on the assumption that people are able to introspect on their cognitive processes and to report the amount of mental effort expended) (Xie and Salvendy 2000, sec. 2.2: Models for Mental Workload Prediction). Most subjective measures are multidimensional in that they assess groups of associated variables, such as mental effort, fatigue, and frustration, which are highly correlated. The ratings scale may appear questionable, however, it has been demonstrated that people are quite capable of giving a numerical indication of their perceived mental burden (Gopher and Braune 1984).

Furthermore, the physiological domain also provides some useful measurements for the recognition of cognitive load, which are based on the assumption that changes in cognitive functioning are reflected by physiological variables (Beatty and Lucero-Wagoner 2000). These techniques include measures of heart activity (e.g., heart rate variability), brain activity (e.g., task-evoked brain potentials) and eye activity (e.g., eye-pupil and eye-blink rate). Psycho-physiological measures can be used to visualise the detailed trend and pattern of load (i.e., instantaneous, peak, average, and accumulated load) (Paas and van Merriënboer 1994, 352). Unlike heart-rate variability and other physiological measures, the cognitive pupillary response seems a highly sensitive instrument for tracking fluctuating levels of cognitive load. Beatty and Lucero-Wagoner (2000) identified three useful task-evoked eye-pupil responses: mean pupil dilation, peak dilation, and latency to the peak. They also found that mean pupil dilation was a useful measurement for cognitive load, especially for young adults. Taking into account the complexity of measuring equipment and technical constraints, the pure psycho-physiological measures were not recommended for the evaluation of this research. Instead, a possible trade-off was seen as combining the subjective analytical methods (questionnaire and interviews) and objective methods (task performance observation and videotaping), and adopting the ratings scale technology based on the questionnaire (NASA task load index) (Table 2; Figure 11). This was proposed since the subjective workload measurement techniques using rating scales were easy to use, inexpensive, and reliable, could detect small variations in workload and provide decent convergent, construction and discrimination validity (Gimino 2002). In addition, the objective measurement techniques were robust enough to conduct susceptibility research and facilitate the experimental results of both subjective and objective analysis (Mulhall et al. 2004).

Table 2. Rating Scale Category Definitions for NASA Task Load Index (Hart 2006, 908)

Category	**Endpoints**	**Descriptions**
Mental demand	Low/High	*How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking and searching.)? Was the task easy or demanding, simple or complex, exacting or forgiving?*
Physical demand	Low/High	*How much physical activity was required (e.g., pushing, pulling, turning, controlling and activating)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?*
Temporal demand	Low/High	*How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?*
Effort	Low/High	*How hard did you have to work (mentally and physically) to accomplish your level of performance?*
Performance	Good/Poor	*How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?*
Frustration level	Low/High	*How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?*

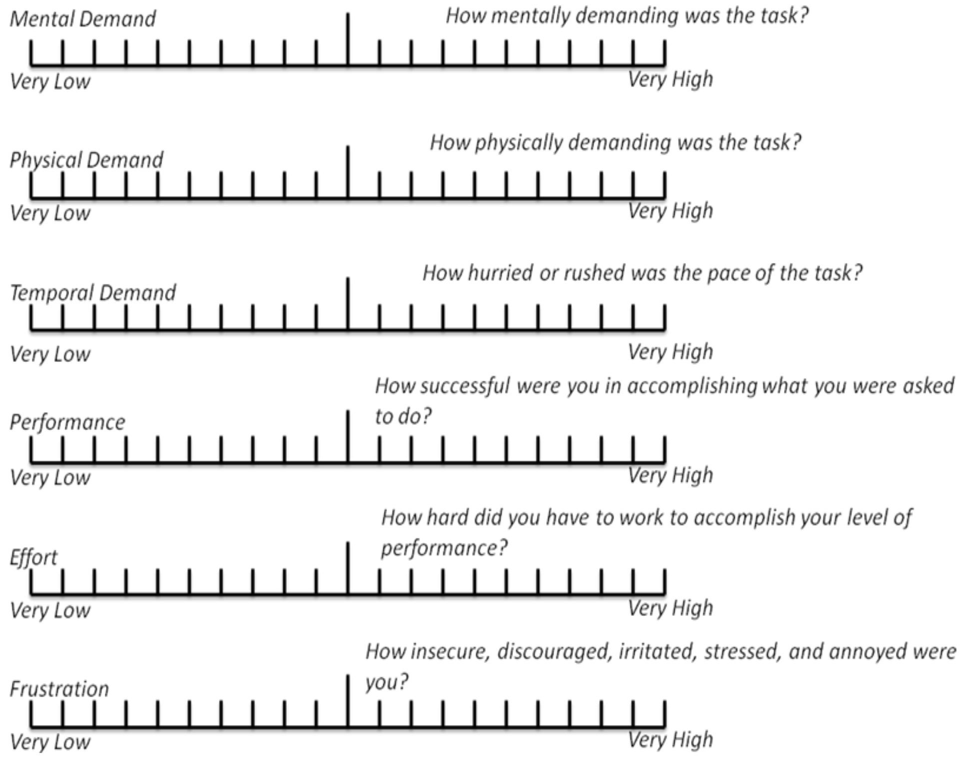


Figure 11. Questionnaire-based NASA Task Load Index. Hierarchical Measurement for Cognitive Workload that Consists of Six Items: Each Refers to the Workload of a Specific Activity (Hart 2006, 908)

- Experimental Design

The two-group, two-period crossover design, which is also known as the standard crossover design was originally planned in the experiment. The main justification for adopting this design was to minimise the effects of the learning curve imposed by the different sequence in presenting the two treatments. In practice, when differential carryover effects (learning curve effect from period 1 to period 2) are present, the standard crossover design may not be useful due to the primary effect being confounded or compromised by the differential carryover effect (Wang, Xiangyu 2006, 97). This is true in this experiment where the two treatments are compared. Methods should influence the performance of each subject. To overcome this drawback, a higher-order four-group, two-period crossover design was eventually used, which comprehensively considered the treatments, period influence, the model differences and group differences. Two treatments and two assembly models led to 4 different combinations as shown in Figure 9. This scheme considers the learning curve effects of the order of two consecutive trials (two combinations) for each subject. This replication ensured that the model was applied to the animated AR visualisation in half the replicates and in 2D drawing/3D manual prints in the other half.

Experiment I consisted of two scenarios for evaluation. Scenario 1 used two sets of LEGO models (model A and B) and Scenario 2 used piping models (model A and B). All the above models were used for AR and manual/drawings guided assembly (we assumed two sets of models within both scenarios were similar in the complexity and difficulty, which was confirmed by the statistical testing discussed in a later section). Within each scenario, each subject used both treatments to assemble two respective models in a specified sequence for each trial.

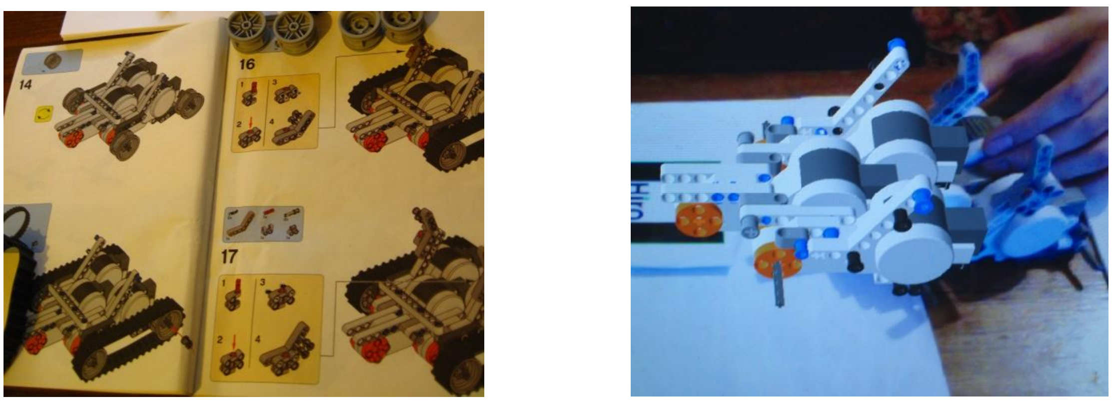
5.5.1. Scenario 1: LEGO Model Assembly

Although previous discussions have focused on the differences between 2D planar images in 2D planar images in drawings, 3D images in manuals and 3D spatial images in AR, the first experiment undertaken sought to isolate the animated AR system's unique advantage by using 3D forms of components as a guide in both cases. Therefore, treatments in scenario 1 were paper-based 3D manual prints where the participants could see the 3D LEGO components and AR animation based instructions (Figure 12). This choice is not an unrealistic one for mechanical assemblers given the increase in the use of 3D modelling. After a mental rotation test, 28 human subjects were screened for the suitability of the experiment. The sample size was decided on the basis of Cohen's *d* benchmark (Cohen 1998). This is the appropriate measure to use in the context of a t-test on means. In this experiment, the value of Cohen's *d* rated as 0.28 (95% confidence interval), was measured on a scale of small to medium size effect of crossover design (0.2 to 0.5). This indicates that in the sample size considered, a minimum of 20 participants in this scenario was significant enough for the purposes of the outcomes of the research. None of them had ever used AR before. Since the carryover effect of playing LEGO toy could be a potential factor that biased the veracity of the data (some of the human subjects, especially the male assemblers claimed that they knew about LEGO blocks), the screening of human subjects in scenario 1 (experiment I) had guaranteed that few of them had the actual experience of assembling LEGO. Moreover, our prototype was derived from the "LEGO EDUCATION SERIES", where the work-pieces were very complicated, and were normally used for industrial application or academic research, all the subjects had never played the LEGO model of such a complexity before. Prior to the LEGO assembly task, the participants in four groups (each group consisted of 7 participants and used different treatments) undertook a training phase, during which they acquired the knowledge about the nature of AR, how to operate the AR animation system and how to read the 3D manual prints. They were then exposed to several pictures of spatial objects and were required to remember them. For example, in the first period, Group 1 used the AR system to assemble model A. When the first period was finished, the participants commenced the second period, but switched over the treatment as well as the model. Meanwhile, the participants were simultaneously prompted to listen for the names of objects interspersed within a string of pre-recorded words presented at 3 second intervals, and they would say 'yes' if they heard a word designating a previously shown image of any of the spatial objects. Two measures were used to evaluate performance and the meanings of these measures were also explained to the trainees.

- Time Consumed to Complete Entire Task

- Number of Errors Committed During Entire Task

Usually, there are three categories of error: component selection error, assembly sequential error and fixation/installation error. Post-experiment questionnaires were designed to be completed based on the subjects' experiences and feelings during the experiment. Two sections were included in the questionnaires (Appendix K).



(a) (b)

Figure 12. LEGO Assembly Using Different Treatments: a) 3D Manual Prints as Guidance (Adapted from Standard LEGO Assembly Manual of LEGO MINDSTORMS NXT 2.0); b) the Animated AR System as Guidance

5.5.2. Scenario 2: Piping Assembly

The following work applied the knowledge gained from Scenario 1 to the real scale construction piping assembly scenario to measure productivity improvements. The main difference between Scenario 1 and Scenario 2 is in the scale. Scenario 1 concerns small-scale assembly on tabletops and Scenario 2 concerns real scale in the real world. In the practice of constructing pipework, isometric drawings are commonly used in construction assembly work. They correspond to the rotation of the object by ± 45°

about the vertical axis, followed by rotation of approximately ± 35.264° about the horizontal axis, and project the shape of the object from three coordinates to one single-sided piece of paper to cater for human visual familiarity. It is not usually the real scale and shapes along each axis of the pipes and fittings that reflect in isometric views. In Scenario 2, one of the treatments simulated a real piping assembly environment, where the participants applied real paper-based 2D isometric drawings to direct the real scale pipework, as compared to the treatment of AR animation-based instructions (Figure 13). After a mental rotation test, 20 human subjects were screened before attendance at the experiment (20 participants was significant enough for the veracity of the outcomes, as the value of 0.28 in Cohen's *d* benchmark represents a 95% confidence interval) (Cohen 1998). Time and error were two critical indicators for evaluating task performance. The composition of time includes: the original time and the rework time. The original time, against the overall time, excludes the time elapsed in error checking and correction. The time taken for rework is parallel to erroneous assembly. In practice, error checks need to be conducted at random times during and after assembly for the identification and correction of erroneous assembly. The scenario designs are in accordance with this principle. The participants were required to examine the assembly process independently, and were allowed to dismantle incorrectly assembled pipes, and reselect and reassemble the correct ones at any time during the task process. A task examiner was also assigned to review the completed assembly and report errors to the participants (but not to inform them as to how to correct them), if errors were not identified by participants. As a result, the participant was able to know where errors were made and rework on them. The parameters for evaluation are listed as follows:

- Time (1 and 2 are for original time; 3, 4 and 5 are for rework time)

1. *Interacting with guidance and examining pipes (operating AR/reading drawings, comprehending and comparing pipes in augmented scene/measuring pipes with ruler, etc.)*

2. *Assembling (lifting pipes, moving to site and assembling pipes)*
3. *Re-interacting with guidance and locating correct pipes*
4. *Dismantling wrong pipes*
5. *Reassembling*

- Number of Errors

1. *Errors of incorrect pipe selection*
2. *Errors of incorrect installation*

- Cost

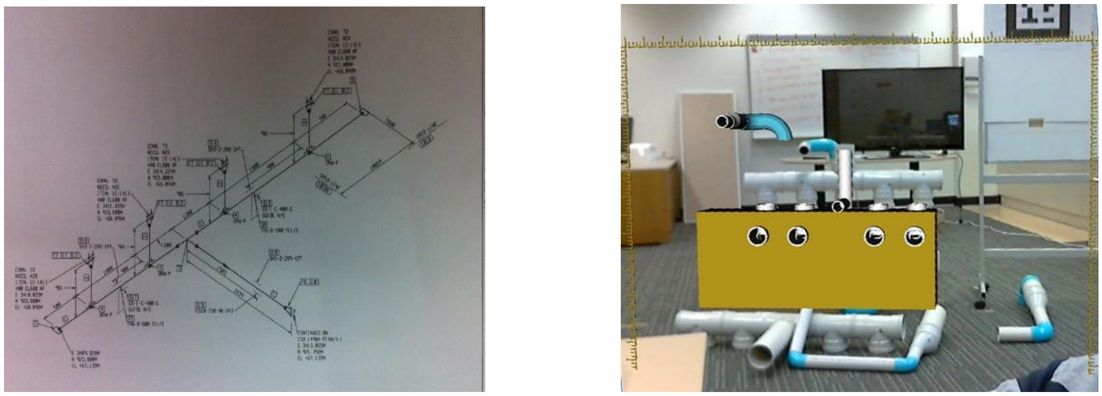
1. *Payment for work on original and rework phases*
2. *Re-welding cost due to dismantling the incorrect pipes or installation*

The rules of conducting the assembly were set in advance to facilitate uniformity in assemblers' work behaviour. All participants were informed of the meanings of the aforementioned measurements (Table 3).

Table 3. Detailing the Rules of Assembly and Metrics for Measurement

Rule	**Description**
Assembly Sequence	*Since AR visualisation provides step-by-step guidance, the drawings applied for assembly instruction abide by the same assembly sequence.*
Step Confirmation	*Connecting two pipes signifies that this specific assembly step has been completed and confirmed by the assembler.*
Rework Definition	*Rework is required when erroneous assembly occurs, where the corresponding rework time and cost will be calculated. Rework involves dismantling the erroneous connection and re-welding the correct pipes. To simulate real assembly (our piping prototype is connected by inserting pipes into one another), each insertion in the experiment corresponds to a welding cost, which is decided by welding length (see Equation 6.3).* *Rework can happen at any time during or after assembly. A task examiner was also assigned to review the completed assembly and report errors to participants (but not to inform them as to how to correct them) if errors were not identified by participants.*
Errors	*Errors occur when incorrect pipes are chosen and installed or when the installation itself is incorrect.* *Assemblers must correct errors by removing the pipes in question and re-welding the new pipes. If erroneous assembly occurs in the final assembly, a once only instance of dismantling is allowed; along with an allowance for re-welding the correct pipe (both for one end only). In other cases, two dismantling and re-welding instances are permitted(one pipe has two ends).*

Post-experiment questionnaires were designed to be filled in based on the subjects' experiences and feelings during the experiment. Two sections were included in the questionnaires (Appendix L).



(a) (b)

Figure 13. Piping Assembly Using Different Treatments: a) 2D Isometric Drawings as Guidance; b) the Animated AR System as Guidance

5.6. Experiment II - Training Effects and Learning Curve

The objective of experiment II (Scenario 3) was to establish learning curves for the two treatments in order to study if there were significant discrepancies in performance between the two groups of trainees, using different training schemes. Learning periods generally exist in assembly work, and a higher order of cognitive activity is typically required in more complex assembly tasks. If assembly can be complex enough to have such cognitive components, then it may be possible to demonstrate this learning period (after which assembly performance improves), and observe the effects of the instruction format on the learning of the assembly task. The work of Baggett and Ehrenfeucht (1991) suggest that dynamic representations presented a superior training media to static representations, i.e., with drawings, the assembly work did not allow for any interaction between the participant and the assembled item. According to Richardson (1996, chap. 1: Evolving Concepts of Working Memory), the central-executive component of the WM is involved in decision-making, which reflects the time it takes the WM to glean and process the properties of the stimulus. The decision-making process applies to motor performance where too much complexity leads to higher error rates. To investigate the learning effects from training via the assembly manual and AR animation, the LEGO model (Model A) used in Scenario 1 was selected as both an experimental training task and an unarmed assembly task followed by training. The span of the WM of trainees depends on the characteristics of the information to be acquired. The established method of digit-span testing is typically regarded as a common way of assessing the WM (Fischer 2001, 143). However, for the assessment of the WM span only, a task called the Corsi Block Task (CBT) (which requires testers to temporarily remember the location of spatial objects), became a predominant method in neurology for assessing spatial memory capacity, especially the visuo-spatial WM span (Kolb and Whishaw 2008). The essence of CBT is to use the method of loci (visual location cues). When conducting the CBT, a tester is presented an item by the experimenter who points sequentially to a subset from among nine cubes on a lattice-shaped image. After that, he/she should recall the sequence of nine cubes with sequential pointing movements according to his/her method of loci. In addition to the intended memory load for sequential order and spatial locations, the CBT involves the encoding of visual stimuli, maintenance of information over time and response selection prior to overt response execution, and each of these processing stages contributes to overall performance (Orsini 1994). In light of this, Scenario 3 requested the trainees to recall the components sequences, spatial position and installation from the assembly guidance offered in the training phase. After this, they were requested to conduct the same assembly in the formal experiment without guidance.

- Experimental Design

This is the same design as the LEGO assembly experiment (Scenario 1 in experiment II). Experiment II also isolated the animated AR system’s unique advantage by using 3D modelling for training. The concern that the carryover effect that might bias the results had been eliminated, since the carryover effect determined by the treatment (AR and manual/drawing), period (treatment sequence) and model difference (model A and B) was proved to be insignificant, as indicated by the statistical data of the LEGO assembly experiment (see Section 6.2.1). It was therefore decided that the four-group, two-period crossover design could be simplified to a between-subject (with two comparison groups) design. This simplification required only one LEGO model (model A) in the training phase. Before experimentation, the trainees were randomly divided into two groups, with each group under a respective training treatment (3D manual training and AR training) and comprising the same numbers of males (14 participants) and females (14 participants). The sample size was decided as significant enough to represent the outcomes of the research on the basis of Cohen's *d* benchmark (Cohen 1998), where the value of *d* was measured as 0.3 on a scale of small to medium size effect. Only one trial was allowed in the training phase, for assemblage of the models, however there was no time limit. In the training phase, the trainees were required to remember the assembly sequence, spatial position and component fixation/installation. After training, they conducted the same assembly without the aid of the guidance given in the training phase.

5.6.1. Scenario 3 - LEGO Model Assembly Training

These 28 human subjects were of a separate selection from those in Scenario 1 of the experiment in that none of them had used AR before. Since the carryover effect of playing LEGO toy could be a potential factor that biased the veracity of the data (some of the human subjects, especially the male assemblers claimed that they knew about LEGO blocks), the screening of human subjects in scenario 3 (experiment II) had guaranteed that few of them had the actual experience of assembling LEGO. Moreover, our prototype was derived from the “LEGO EDUCATION SERIES”, where the work-pieces were very complicated, and were normally used for industrial application or academic research, all the subjects had never played the LEGO model of such a complexity before. Basic training, following the manuals/animated AR system, was limited to one single LEGO model (model A) assembly cycle without a time limit. The test trainees were required to remember the assembly sequence and component fixation/installation. After the basic training was completed, the trainees relaxed for 5 minutes and were given reading material unrelated to the experiment such as newspapers. During this period, the assembly manual/AR system was removed and the model pieces were laid out on a table. The two test groups of 28 students then started their first trials without manuals or AR. Three measures were used to evaluate performance, with the meaning of these measures explained to the trainees:

- Number of Assembly Trials Permitted Until Assembly is Completed Without Errors
- Time Consumed to Complete a Trial
- Number of Errors Made during a Trial

The number of trials indicates how many trials a trainee needed before completing assembly thoroughly without error. Usually, there are three categories of error: component selection error, assembly sequential error and fixation/installation error. However, a protocol had been set up, based on the behaviour of requesting former guidance, which was also counted as a category of error since trainees might err if no guidance was provided. After each unsuccessful trial, the number of errors was totalled up and the results given to each trainee, allowing each trainee to check the steps where the errors had occurred. Subjects were videotaped during their task assignment so that potential errors could be identified. Since there was no guidance or information available, trainees had to mentally retrieve information and recall the assembly steps from their WM that had been developed in the training sessions.

5.7. Introduction of the Chosen Assembly Tasks

The choosing of assembly tasks was very important to the veracity of the experiments. There are many ways to choose tester tasks. The method adopted here was to choose the assembly task based on a self-developed hierarchical taxonomy, which classified the cognition-demanding assembly tasks. In order to map the appropriate AR technology to general assembly tasks, it was necessary to analyse assembly tasks according to their common functional aspects. One approach to characterising tasks, activities, or operations involved in assembly tasks is to examine general and fundamental tasks which in effect, serve as common denominators for the analysis of more complicated assembly activities. All assembly tasks require performance of some information-intensive basic activities and those activities are crucial in the following taxonomy, which breaks construction and manufacturing assemblies down to activities based on different levels. The four major objectives in developing assembly task taxonomy are listed as follows:

1. Identifying the opportunities for exploiting AR visualisation according to analysis assembly tasks in multi-levels

2. Developing a methodology for mapping AR visualisation according to examining the mental perspective of assembly tasks

3. Validating the theoretical model raised in this dissertation based on the proposed theoretical mechanisms of the animated AR system, as depicted in the section 3.3

4. Enabling the general user to make use of AR designs

- Hierarchical Taxonomy of General Assembly Activities

As depicted in Figure 14 and Table 4, there are four categories of assembly activities in the taxonomy. Understanding the hierarchical nature of composite and primitive activities may illustrate the common ground assembly tasks have in the construction assembly domain, while the subtasks within them may help this research identify potential user-centred goals and set representative assembly tasks. The formerly elaborated potentials that the animated AR visualisation could offer may conclude that the composite and primitive levels are the ones where animated AR visualisation technology is more suitable as an application. The mental tasks involved at these levels are where analysis and research should be focused. Once the mental activities at this level are understood, an assembly information processing model can be formulated for the respective tasks, which can then be analysed to reveal the issues involved in human cognition and validate the proposed theoretical framework. Also such mental activity analysis can assist in selecting AR visualisation representation, AR interaction mechanisms, and even tracking technology. The matter of this selection is elaborated upon as the reasons for establishing the mapping model in the next section.

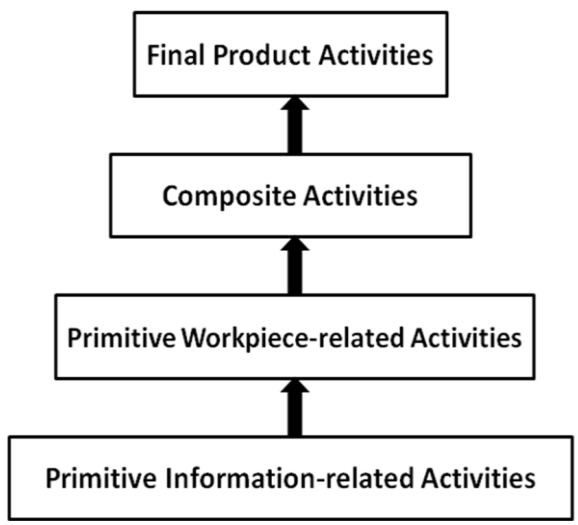


Figure 14. Hierarchical Taxonomy of Assembly Activities

Table 4. Detailing the Hierarchical Taxonomy of Assembly Activities

Level	Description	Examples
1	Final Product Activities	*maintenance, fabrication, repair, testing, inspection, interference checking, assembly evaluation, commissioning*
2	Composite Activities	*retrieve, comprehend, memorise* *connect, fasten, install, fix, align*
3	Primitive Work-piece-related Activities	*reach, grasp, select, compare, measure, grasp, move*
4	Primitive Information-related Activities	*retrieve, comprehend, filter, memorise*

1. *Final product activities:* As indicated in the literature review, AR visualisation has already been promisingly applied in product maintenance, repairing, inspecting and checking for interference. However, it has been rarely used in fabrication, testing, assembly evaluation and commissioning.

2. *Composite activities:* Composite activities are the fundamental construction blocks of assembling products. They are the combination of work-piece-related activities and information-related activities, and involve the 'actual assembling or installing' actions. Within each activity, the to-be-assembled component or a cluster of component units is connected or installed with the already-assembled counterparts by following a series of assembly rules that comprise assembly craft. The activities actually refer to the integration of perceptual, cognitive, and motor behaviours. The first two types of behaviour are primarily mental processes, which typically precede motor responses. For instance, the assembler needs to understand the ways of component fixation or installation from the guide before they actually act.

3. *Primitive work-piece-related activities:* Primitive work-piece-related activities, directly interact with the individual component itself such as selecting, reaching,

grasping, moving, etc, unlike the 'actual assembling or installing' actions that occur in composite activities. In this research, the level of primitive work-piece-related activities is the lowest motor level to be analysed.

4. *Primitive information-related activities:* Primitive information-related activities refer to elementary perceptual and cognitive processes such as retrieving, comprehending, filtering and memorising assembly clues from certain guidance means. The level of primitive information-related activities is the lowest mental level to be analysed.

The major point conveyed above is that in assembly tasks, the more fundamental the applicability of activities, the more frequently they can occur in higher-level activities. Primitive information-related activities such as retrieving and comprehending information from visualisation perform the function of cornerstones for primitive work-piece-related activities such as selecting and measuring the to-be-assembled components. However, both activities are used for implementing the following 'actual assembling process' and finalising product assembly, (outlined in the composite activities and final product activities).

- Mental and Motor Requirements of Assembly Tasks

The mental requirements of assembly tasks concern perceptual and cognitive activities. Perceptual activities are those attributable to sensory comprehension of the visualisation means of assembly guidance, and cognitive activities are those involved in the reasoning and volitional processes that go on between perception and actual actions. Motor activities are those actions due to the selection and execution of physical responses. Table 5 breaks down the mental and motor activities and analyses what kinds of perceptual, cognitive and motor activities are involved in the general tasks, to which the animated AR visualisation may contribute.

Table 5. Breakdown of Mental and Motor Activities (Adapted from Wang, Xiangyu 2006)

1	Perceptual Activities	*detect, retrieve, inspect, scan, observe, survey, read, discriminate, locate and identify*
2	Cognitive Activities	*calculate, interpolate, categorize, itemize, compute, tabulate, encode, transfer, analyse, estimate, choose, predict, compare and plan*
3	Motor Activities	*activate, lower, close, move, connect, press, disconnect, raise, hold, set join, align, track, regulate, transport and synchronise*

Here are examples of how AR can augment mental and motor activities:

1. *Component recognition and detection:* Identifying a component of interest among a cluster of components and highlighting it to influence the user's focus of attention. For example, striking colour, arrows or flags can be used to direct attention to specific work-piece features.

2. *Component discrimination:* Improving an operator's ability to discriminate. For example, a simple grid can be overlaid onto a real view of the site layout to help the worker better understand the spatial relationships between items of interest.

3. *Component comparison and selection:* Real-scale virtual components are able to spatially coincide with the physical components. Being registered into reality, the virtual counterparts of real objects could be defined as real-scale in size and observable (each facet of virtual objects is visible) through rotating markers, which lowers the difficulty of understanding assembly operation and may reduce error.

4. *Component installation:* Special hints help assemblers to confirm the matching relations in spatial position, and they also provide them with proper assembly methods and previously defined paths in the event the to-be-assembled components spatially interfere with the already-assembled components. The diversified

supplemented augmentations in the AR animation prototype are generated to facilitate ongoing tasks.

5. *Recall of assembly context:* Framing memory associations that aid assembly recall can be assisted with a 3D model of a particularly complicated piece of the structure directly superimposed onto its real counterpart. The importance of spatial consistency of objects relative to the real-world coordinate system can be met by registering the to-be-recalled objects right onto the environment.

- Construction Assembly Analysis

The abovementioned features of traditional assembly tasks illustrate the common ground of assembly tasks in the construction arena, which is a type of representative assembly that was scoped as the focus of this research interest. In construction, assembly is a process where workers refer to technical specifications (information activity) to obtain the right information (information activity), identify components (work-piece activity), place the component, compare the standards (work-piece activity), and then make a judgment as to its correctness (if necessary, rework may be required). The entire process is iterative and repeated and a learning process is triggered which may lead to improved proficiency as cycles are repeated. An inability to find the correct materials or an incorrect sequence in a cycle can contribute to productivity losses for an assembly operation. Construction crews rely heavily on paper-based documents to access and record information, which can be cumbersome and labour intensive and this increases the propensity for errors to be made. Therefore, the way in which assembly information is presented to an assembler influences operational effectiveness. There are *four* main issues in construction assembly: 1) not being able to find the right information contained within technical drawings; 2) not being able to find the correct component to be assembled; 3) an incorrect assembly sequence; and 4) incorrect installation.

An example where assembly problems may arise occurs during the installation of HVAC piping (e.g., skid). Workers are required to measure the available installation and workspace, read from the technical drawings, find and identify exactly the right pipe component, decide on its appropriateness, install and then check that all is in order. Similarly, the rebar assembly usually takes place in a prefabricated shop prior to being delivered to the site for concrete pouring. The most commonly occurring issue in rebar assembly is that workers spend a considerable amount of time trying to find the right length and diameter of rebar to install. The assembly sequence is also crucial, as the incorrect placement of HVAC pipe/rebar can inhibit access to a space inside a welded structure. Workers usually read the pipe/rebar plans, find the piece, place and weld it, and then check all is in order. One proven and efficient way to identify a piece is through colour coding with different flags to differentiate size and type. Workers can then easily identify the correct pipe/rebar by colour identification. This method, however, does not address the assembly sequence and path that are adopted. Construction concrete wood formwork also involves similar procedure and issues. Workers first read the concrete plan, measure the site, select the right formwork in the stock area (formwork looks very similar to other materials in surface and size), install it in place and then check that all is in order.

The insertion of digitalised assembly information into the real workspace using AR can provide workers with the means to implement correct assembly procedures with improved accuracy (Wang, Xiangyu and Dunston 2006, 322). With this in mind, this paper designed and developed an animated AR system to guide assembly tasks to reduce errors and improve operational efficiency. A prototype-animated AR system is configured for assembly tasks that are normally guided by reference to documentation and tested using a series of experiments. The proposed system can facilitate the transition from paper-based knowledge manual systems (information activity) to work-piece activity by complementing human associative information processing and memory. This dissertation specifically explores the following cognitive aspects associated with AR and assembly: information retrieval; frequency of attention switching; the WM; likelihood of error; spatial cognition association and learning or recall from training.

Construction assembly, as a specific type of procedure-related task, has a reasonably similar expectation of benefits when facilitated by AR. The dissertation also chose a LEGO assembly and piping assembly as the test bed, and tester tasks to validate the cognitive benefits of AR for the assembly process, based on the following reasons and justifications:

1. *There is a high level of similarity in the principles of the procedures between LEGO assembly and construction assembly:* 1) they all have the four assembly issues detailed previously; 2) workers search a medium (e.g., paper manual, technical drawings) for information, which is a highly-demanding cognitive information activity; 3) workers have to search for the right component in the material stock area, according to the information found in the relevant medium; 4) there is a high level of head, eye and hand movement along with consciousness of time-keeping; 5) multiple tasks are involved, being information and work-piece activities; 6) there is a great deal of attention-switching between information and work-piece activities, involving 'overhead chores', such as retrieving 'rules' associated with each task; 7) tasks rely heavily on the use of working memory; and 8) when tasks are repeated frequently, workers can become experts in those tasks through the combination of low performance variability and 'overlearning'.

2. *LEGO assembly can be a reasonably downscaled and controlled version of real scale construction assembly:* Distracting factors can be controlled in the experiment in order to focus on studying the specific cognitive features of AR for assembly. It is easier to control and implement than real assembly, but still involves similar principles of assembly to those found in construction.

3. *The current focus of this paper is to study the cognitive aspects of AR as it relates to the nature of assembly, regardless of the type of assembly itself:* Knowledge gained can be used to better devise and design experiments for larger and more practical experimentation involving access to the site, equipment, and materials of practical construction assembly. This will be the focus of the next step in the experiment.

4. *From a practical point of view, the assembly tasks selected for the experimental evaluation should be selected to align with the practical application in the construction arena. They must also be representative and able to reveal the various effects of different assembly guidance. However, the safety and manoeuvrability considerations in the experiments restrict the sizes of the assembly product.*

The small scale LEGO MINDSTORMS NXT2.0 (Figure 15a) was selected as the experimental content for the animated AR system due to each component's dimensional disparity (e.g., shape and colour). When installing pipes, the measuring g is relatively cognition-demanding; whist the task itself overemphasises the assembly sequence or installation/fixation. Real scale piping assembly tasks (Figure 15b) seem to be operationally adaptive and appropriate for investigating the respective cognitive workload resulting from two ways of pipe parameter measurement (monitor-based comparison using the AR system versus assembly manual-based measurement). In addition, both assembly tasks are suitable for the purpose of experiment I, which is to study a human subjects' performance in merging digital virtual information (e.g., animated AR guidance) with the requirements of a real assembly workspace and based on the nature of a person's cognition, compared with merging physical information (e.g., a manual) with the requirements of a real assembly workspace. Along with the dimensional disparities of each component, both models also differ in terms of shape and colour. This demonstrates that the assembly sequence and component installation/fixation are likewise conceived to be critical issues, other than component selection only.

(a)

(b)

Figure 15. A Snapshot of LEGO Components (Adapted from Standard LEGO Assembly Manual of LEGO MINDSTORMS NXT 2.0) and Piping Components

For experiment II, the task selected should be complex enough to give rise to high demands on human cognition. Therefore, same LEGO model was chosen to be used as the content for experiment II for the animated AR system. The LEGO model consists of 35 spatially functioning pieces and some of them have particular characteristics in terms of shapes and colours. These components are dismantled in advance and kept in the work-piece stock area'. The complexity of tasks is determined in the pilot study, where ten participants were recruited to assemble the model. The participants read the guide and then it was removed. Without the guide to assist them, none of the participants were able to complete the model assembly within 20 minutes (20 minutes was defined as the threshold of complexity). The subjects were also permitted to assemble the model in any way they chose but even with this option, none was successful. The task difficulty matched the needs and requirements of the experimental design. Some components were similar in shape but different in dimensions and therefore task completion was expected to be based on memory recall of the training material.

5.8. Prototyping the Animated AR System

- Design Principles of the Animated AR system

From the theories mentioned above, five design principles are identified for addressing the conceptual feasibility of using the animated AR system in the assembly work process. They relate to how information is obtained, how 'guiding effects' and 'training effects' are evaluated, distraction from other tasks, and the function of memory. Each of the five design principles are explained as follows:

1. *Correctly conceptualising the assembly context in terms of component contents and user action. This would be paramount in making conscious cognitive assertions of fact, eventually leading to the retrieval of assembly information and decision making:* AR technology is suitable for information-intensive tasks which usually deal with information transfer and the transposition from paper instruction to the work itself. During assembly tasks, being guided with visualisation from AR, it is intended that the assembler utilises the advantage of the interface that promotes more effective use of both visual stimuli and motor actions. The AR interface lends itself well to task-related learning/training because of the exclusive connection between

short cycles of visual perceptual activity and physical movements. This provides the user with advantages for action in the world, and physical processes that involve action (Shelton and Hedley 2004, 334). Maintenance and manufacturing experience is filled with evidence that people favour information that is easy to access and they tend to use more active elements in decision making (Yoon and Hammer 1985). AR can augment a human's ability to access information and documentation in the course of performing their work and thus it enhances the individual's decision-making ability.

2. *Helping evaluate the 'guiding effect' in the ongoing assembly task, compared with 2D drawings/3D manual prints, due to the dual visual and physically interactive nature of the animated AR visualisation:* Moving elements in the environment may affect the way a person interprets the purpose of the objects within that environment (Shelton, Humble and Matson 1996). In active vision theory, the nature of the visual image cannot be separated from the action of the individual who perceives the image. It is important to concentrate on how the visualisation is used in the process of learning/training and how different visual representation is utilised by users possessing different information under assembly guiding and training scenarios.

3. *Helping evaluate the 'training effect', compared with 3D manual training. Due to the dual visual and physical interactive nature of animated AR visualisation, it is expected to aid information recall for a specific training purpose:* Winn and Snyder (1996) focused their visualisation research on how the trainees impose their own structure on incoming information for more effective learning. They regarded this process as 'information mapping'. The findings includes that the trainees presented significant improvement of organising content, presenting spatial layout and recalling spatially presented information. Resembled findings from VR research have also provided a recommendation for graphical layout and pictorial representations of instructional visualisation (Winn and Windschitl 2002).

4. *Helping to facilitate information-related activities (cognitive processing) and work-piece-related activities (manual processing) to happen essentially concurrently, with the intention that animated AR visualisation will lessen the total task time. This result is the type of benefit envisioned by using AR visualisation in assembly, especially cognition-demanding tasks:* Animated AR visualisation should lower the frequency of switching between activities and information resources by integrating information retrieval processes and work-piece operational processes, therefore reducing the time associated with the cognitive activities demanded in repetitive switching. This is paralleled with the fact that cognition time was independent of manual time (time for actual manipulation of devices and instruments) and individual workers differed in how much time they devoted to cognitive/informational chores, but differed little in how much time they devoted to manual chores (Towne 1985). In addition, it is easier to alternate between versions of the same task than to switch between different tasks, which gives rise to 'overhead chores', such as the retrieving 'rules' associated with each task.

5. *During training, help trainees memorise the assembly information accurately with a view to minimising the activities that intervene between the presentation of the information and memorising:* Animated AR visualisation is a promising technique to bridge the above gap and improve post-training performance by forming a memorising learning curve. The design principle of the AR system should also include: directly inserting the required information into the worker's real world view of the task, and easing access to the part of the short-term memory occupied by those items. In this way, the capacity for efficient retrieval of information from the formally created short-term memory is improved.

- Physical Factors in Influencing the Prototyping of the Design of the Animated AR System

For the purpose of producing a successful AR system, many influencing factors have been identified from a thorough observation of AR systems prototyped in many related domains, such as mental endeavour, physical disposition, sense of immersion, surrounding environmental setup, equipment selection and occupation of human movement. From the perspective of the feasibility and suability of AR technological components (representation of visualisation, input mechanism, output mechanism, tracking technology), Wang (2006, 41) pointed out that at least four factors should be seriously considered in designing a sound AR system for operational tasks, which are mental effort, physical disposition, surrounding environmental setup and occupation of human movement. Table 6 outlines the physical mappings between these influencing factors and the AR technological design components of animated AR visualisation.

Table 6. Mapping Influencing Factors of AR System to Technological Components (Adapted from Wang, Xiangyu 2006, 41)

Influencing Factors (Task Side)		**AR System Technological Components (AR System Side)**
Mental Effort		*Sense of Immersion, Representation of Visualisation, Resolution, Tracking Fidelity and Graphical Stability*
Physical Disposition		*Space Occupation, Input and Output Metaphor, Equipment Weight and Volume*
Surrounding Environmental Setup		*Anti-interference of Lighting, Noise and Hazard Level*
Occupation of User Movement		*Webcam and Marker Disposition, Workbench Layout and Wire Distribution*

5.9. Animated AR System Prototype

The theoretical foundation proposed in Chapter 3 draws upon spatial cognition, active vision and the WM theory, and helps in the understanding of the AR approach in terms of task guiding and training. This section presents an overview of the animated AR system and highlights the compelling and characteristic aspects of the AR interface, linking them to theory presented above. Following this, an integrated view of these aspects, and the relationship to the AR system application in the LEGO model assembly setting is provided. Having laid out a number of theoretical propositions in Chapter 3, and highlighted the important assembly features based on the taxonomy of assembly activities in the ‘assembly task analysis’ session, it can be indicated where the components of cognitive theories fit into the real-world animated AR system, (as depicted in the ‘mapping model’, which maps human cognition of AR technology, see Figure 16).

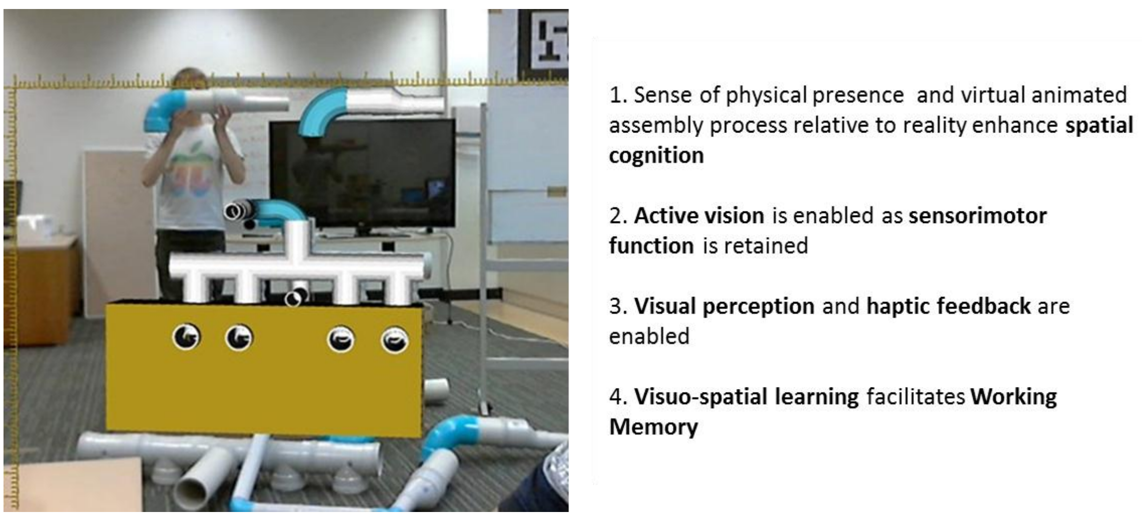


Figure 16. Mapping the Cognitive Framework to the Animated AR System

A prototype-animated AR system for improving the construction assembly process using marker registration technology and visualisation was developed and presented. The proposed system for assembly provides information on the components to be mounted and outputs to be assembled ‘step-by-step’. In this way an assembler can monitor their progress and ensure that they do not damage components that have already been installed. The proposed prototype involved the ‘traditional’ establishment and implementation of an AR, including a computer monitor, predefined paper-based markers, interactive computer graphics modelling, animation and rendering software (3DSMAX), ARToolkit and attached OpenGL. Via the ARToolkit, the virtual images of product components can be registered onto predefined markers and captured in the view of monitors, using HMD or a computer screen using marker tracking cameras.

The virtual counterparts of real entities are acquired from 3DSMAX and then plugged into the ARTookit via a graphical interface. The locomotion along virtual assembly paths for each virtual component and the method of assembly are registered into the real components by using the ARToolkit and paper-based markers. The significant parameters of the ‘to-be-assembled’ and ‘assembled’ objects are graphically identified in accordance to their part/component texture, weight, color and specifications.

5.9.1. Hardware and Software Setup of LEGO Assembly Task

- Hardware Setup

The hardware setup of the animated AR system is depicted in Figure 17 and the details are described below.

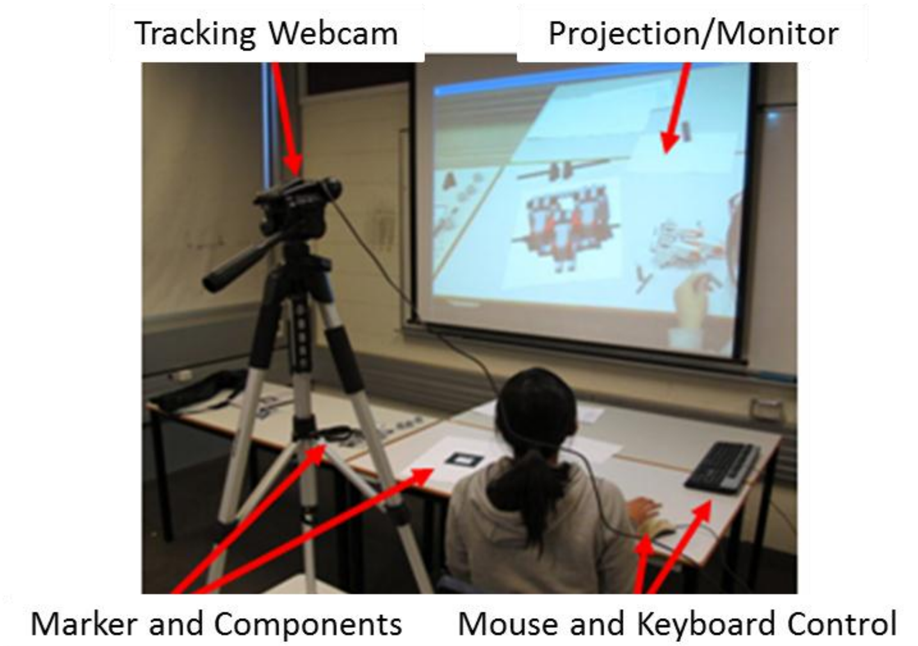


Figure 17. The Hardware Setup and Real Layouts of LEGO Assembly for Scenario 1 in Experiment I and Scenario 3 in Experiment II

1. *Workbench (assembling area):* This is where the assembly process is executed and the markers are positioned. The size of the workbench is large enough to hold the product components and the markers. When the assembly starts, assemblers can lay the markers on the surface of the workbench so that the AR animation can be shown on the monitor. The workbench also enables assemblers to observe from different angles and facilitates operations from various positions.

2. *The position of the monitor and manual:* The monitor is aligned with the position of the workbench and assemblers, on the upper edge of the workbench. When an assembly task commences, assemblers are able to execute the assembly process while constantly watching the monitor. As a result they can focus on the augmented scene displayed and the live tasks on the monitor. This setup eases mental workload

and reduces visual transition when implementing assembly tasks. A mouse and a keyboard provide assemblers with easy control of the animation course, as they can play, pause and replay the animation as well as move the virtual images in augmented scenes. By rotating the markers or keyboard controls, different angles of augmented scenes can be observed by the assemblers. As a counterpart to the AR system, the manual system is positioned on the right of the workbench and braced by a bracket, providing a text manual procedure of assembly guidance. When implementing the LEGO model assembly task, assemblers are urged to frequently switch their attention between task and instruction, and to 'page up' or 'page down' to retrieve information from different pages.

3. *Tracking webcam:* The tracking webcam is a *Logitech Webcam Pro 9000 HD,* which ensures a High Definition (HD) view with autofocus. It projects to the rotatable workbench in a way that overlaps the webcam view and a participant's field of vision. The images of virtual components and the real components are captured by the webcam so that assemblers are required to focus only on the augmented scene identified on the monitor. By tracking the predefined markers, the customised animated guidance can be displayed on the monitor. The angle between the webcam projection and the horizontal workbench is fixed in this instance, which should ensure that the webcam is able to capture the black frame of the markers and the assemblers' manipulation.

4. *Paper-based markers and components:* Markers are all calibrated using the ARToolkit. A main marker is used to animate the process throughout the entire product assembly, while other markers can be added to cater for specific purposes, for example, an ancillary marker with pattern '人' is set to present the virtual layout of the to-be-assembled components. All markers are provisionally placed on the left of the workbench ready to be transferred onto the workbench if necessary. Similarly, the 'to-be-assembled' physical components are also placed on the left zone of the

workbench, which is the ‘work-piece stock area’, as depicted in Figure 17.

- Software Setup

Conventional AR environments are based on the ARToolkit where virtual objects are usually drawn using pure drawing functions of *OpenGL* (Open Graphics Language), a multi-platform high-level 3D graphics API (Application Programming Interface). However, if users want to build their own models, they must acquire knowledge on OpenGL. For the purpose of facilitating use by the layperson without OpenGL knowledge, some AR systems have realised the process of direct loading of varieties of model files, such as BuildAR, AR Media Plugin, D’Fusion and so on. The aforementioned systems cannot be customised to fit the experimental requirements of the research undertaken in this paper. Thus, it was decided to redevelop a set of functionalities that could dynamically load model files into the proposed AR system. Akin to other AR systems, the proposed animated AR system is a user-centred interface between the ARToolkit and any 3D modelling software that utilises ‘.3DS’ files such as 3DSMAX, MAYA and CINEMA4D. In addition, animations can be directly imported into the AR interface via the attached exporters of 3D modelling software, and they can be recognised by the predefined markers without a more sophisticated exporter such as OSGExp. The standard materials and rendering effects can be securely conserved after being exported. A multi-marker was adopted to enable an AR interface, with the synchronous display of multiple virtual objects for assembly purposes.

- Contents Creation of Virtual Assembly Animations

The assembly sequence and component installation/fixation are deemed to be of critical importance along with component selection. The LEGO model used consisted of 35 spatially functioning pieces (Figure 18). These components were dismantled in advance and positioned in the ‘work-piece stock area’. Ten participants were recruited for a pilot study to attempt the LEGO model assembly. They were presented with the assembly manual which was then removed prior to initiating the assembly process.

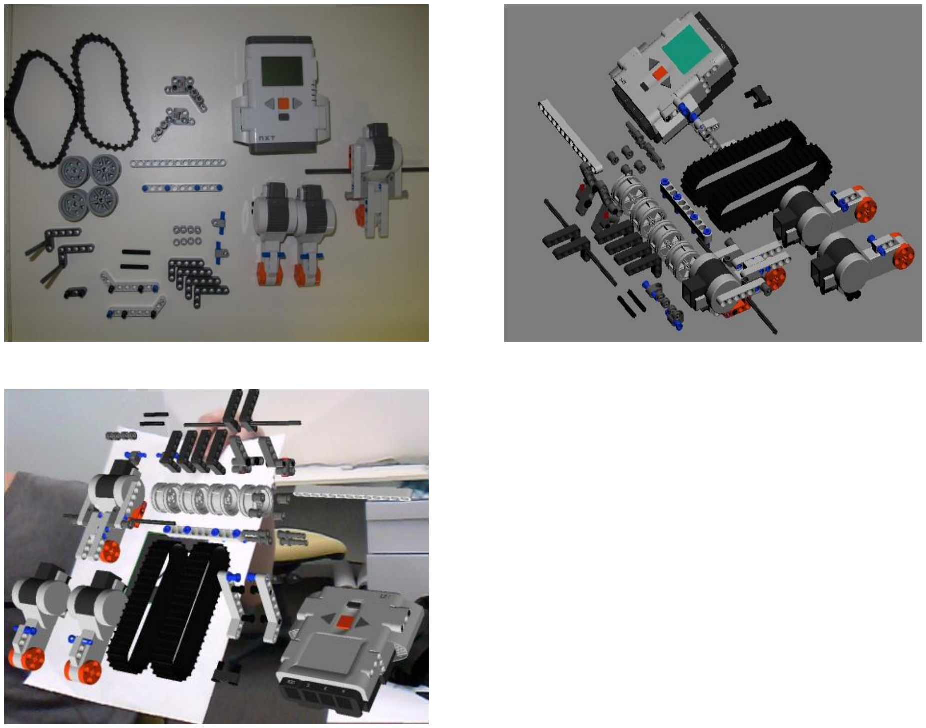


Figure 18. Panorama of 35 Components of LEGO Model in Real Environment, 3DSMAX and the Animated AR System

The participants read the guide and then it was removed. Without the guide to assist them, none of the participants were able to complete the model assembly within 20 minutes (20 minutes was defined as the threshold of complexity). The subjects were also permitted to assemble the model in any way they chose but even with this option, none was successful. The task difficulty matched the needs and requirements of the experimental design. Some components were similar in shape, but different in dimensions, and therefore task completion was expected to be based on the recalling of the training contents. The following three aspects of the animated AR system present the mapping of facilitations:

1. *Real-scale virtual components are able to spatially coincide with the physical components:* In conventional assembly manuals, the component images are typically down-scaled or smaller than the physical components, due to the limited size of assembly manual prints. The implementation of the component/part selection process typically depends on the dimension labels marked in the assembly manual, or on the similarity of component images and physical components. It is sometimes difficult to understand the component's shape in an assembly manual along with the interrelation between components. It is also a challenge to visualise the spatial structure of a product when comparing different views. Essentially, the problems associated with information retrieval from conventional assembly manuals can be overcome by using AR techniques. Virtual counterparts of real objects can be defined in real-scale size and observed (each facet of the virtual object is visible) by rotating markers, which improve an assembler's understanding of operations. In the LEGO model assembly for example, 35 components were different in colour or approximate sizes, but users were able to select components correctly by comparing the real and virtual images of different parts (Figure 19).

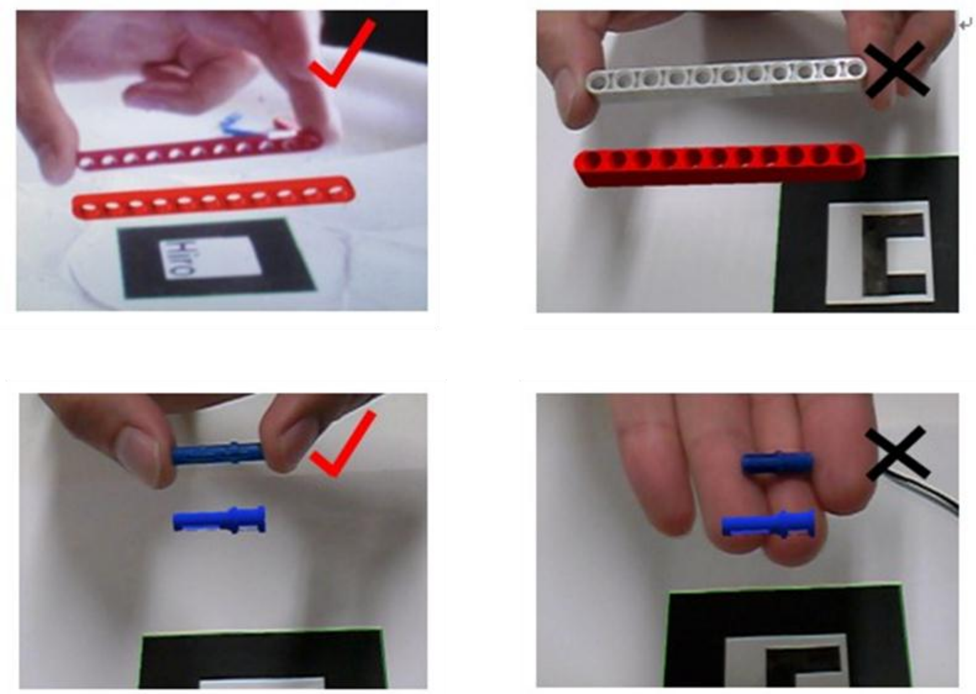
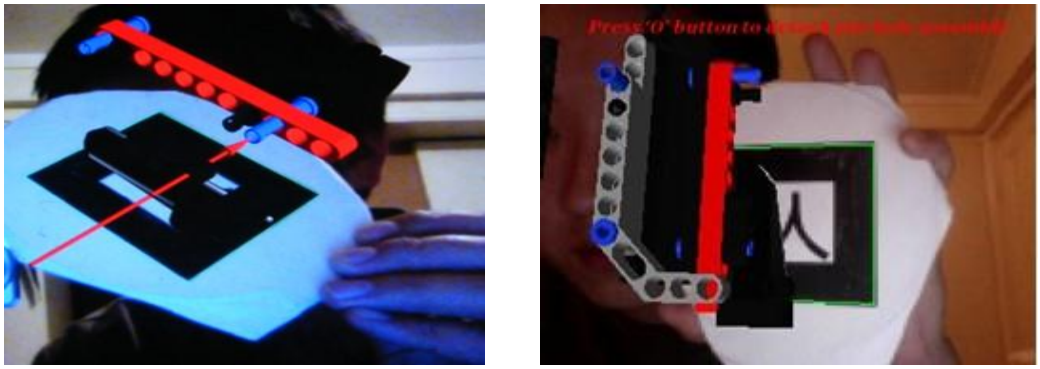


Figure 19. Components Matching and Mismatching in terms of Shape and Colour

2. *Supplemented augmentations ease on-going tasks:* Special hints are applied as supplemented augmentations under specific circumstances, for example, a red arrow in the pin-hold assembly helps assemblers to confirm the matching relationships in a spatial position. For instance, the third hole from the right of the red piece matches the first hole from the right of black piece (Figure 20a). The hints also provide the assemblers with the recommended assembly method. This recommendation is provided to ensure that 'to-be-assembled' components do not spatially interfere with the 'already-assembled' components. Function keys such as 'O' on the keyboard are supplemented to dismantle the pin-hold assembly in the AR environment if the assemblers do not determine how they can match (Figure 20b). The diversified supplemented augmentations in the AR animation prototype are generated to ease on-going tasks.



(a) (b)

Figure 20. Supplemented Augmentations to Ease Ongoing Tasks

3. *Stepwise guidance creates a framework of association that aids assembly recall:* As previously described, AR animation creates a framework of association that aids recall commonly referred to as *spatially augmented stimuli.* These stimuli together may form a framework when subjects use a classic mnemonic technique, the method of loci, to remember a list of items (Neumann, Ulrich and Majoros 1998, 7). Each association of a virtual object with a sequential work-piece feature is a basis for linking memory pieces in human memory. In the animated AR system, when each augmented step of assembly becomes represented in the next one (Figure 21), memory activation will spread through the connection until the whole memory chain is established. This may increase the subject's performance in sequential recall. This could possibly be explained by proficiency, memory and knowledge differences that exist between novices and experts. Memory capacity is a capacity that may help an expert assembler mentally construct the contents without actually spending too much time on retrieval from a physical media. Due to the differences in an individual's capacity and strategy in handling memory pieces or short-term memory store, there is a difference in terms of the effectiveness of retrieving the memory of the previous information. The stepwise guidance enabled by the AR animation form may

facilitate the linkage of short-term memory pieces, and thus be able to improve ergonomic performance by impacting on recall capacity.

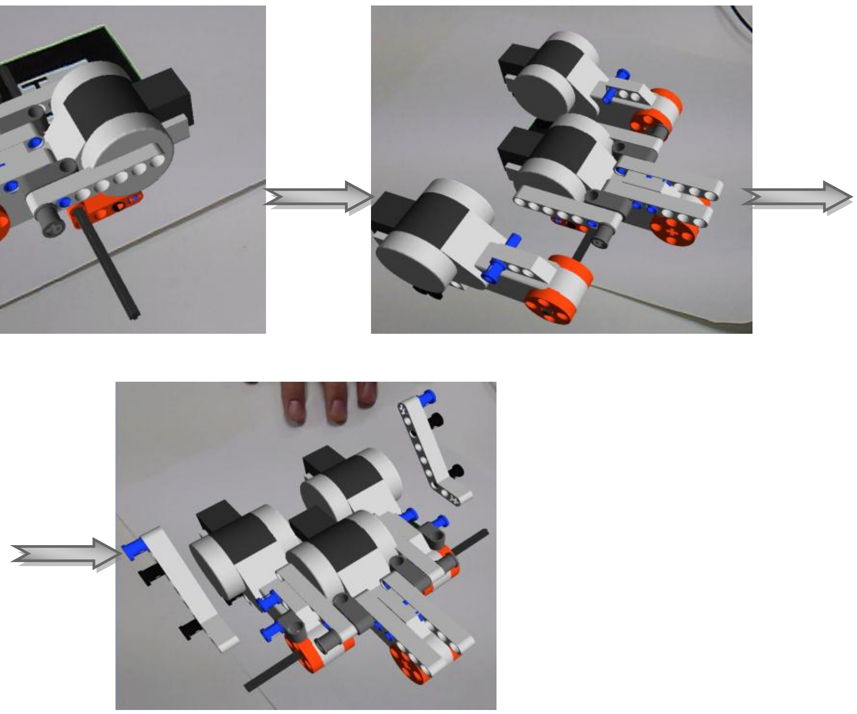


Figure 21. Model is Assembled Step by Step: Completion of Middle Part, Left and Right Parts and Lateral Parts

<u>5.9.2. Hardware and Software Setup of Piping Assembly Task</u>

- Hardware Setup

The hardware setup of the animated AR system is depicted in Figure 22 and the details are described below.

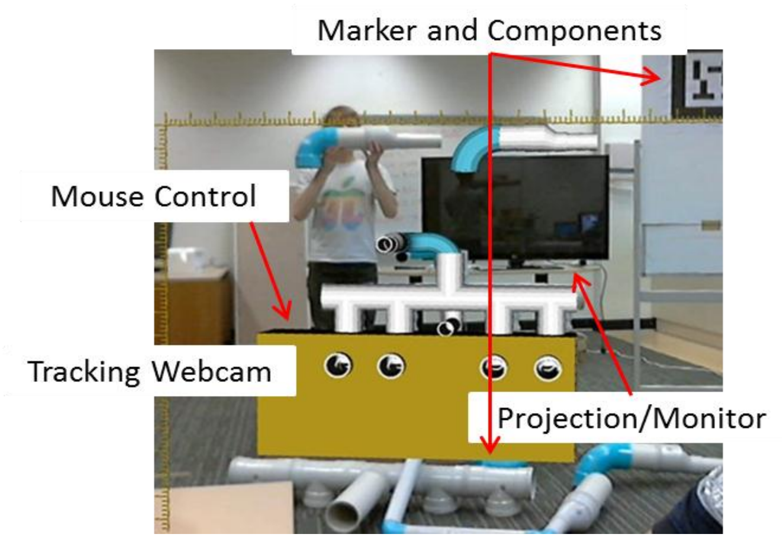


Figure 22. The Hardware Setup and Real layouts of Piping Assembly for Scenario 2 of Experiment II (Virtual Component and Real Component Can be Compared in Monitor View)

1. *Assembling zone:* This is where the assembly process is executed and the marker is positioned. The size of the assembling zone is a $2 \times 2\ m^2$ square in the laboratory of the Faculty of Built Environment in Curtin University, large enough to sustain the product components and the marker. The assembling zone also enables the assembler to observe from different angles and facilitate operations from various positions. To facilitate the review process, this site enables the assembler to scrutinize the detailing of assembly by walking into the model, zooming in and out and looking around.

2. *The position of monitor and isometric drawings:* The monitor is set in front of the assembly zone, 5 meters from the pipe model. When the assembly starts, the assembler is able to execute the assembly process while constantly watching the monitor and focusing on the augmented scene displayed. A wireless mouse is

provided to the assembler; this has remote control of the animation course, and allows the user to play, pause and replay the animation and move the virtual images in the augmented scene. A large set marker and a small moveable maker are needed, as the former is firmly set in space, demonstrating the entire assembly scene, whereas the hand-held small marker is freely manipulated in the assembler's hand, presenting the different viewpoints of the assembly scene. As the counterpart of AR system, the isometric system is positioned to the right of the assembling zone, and braced by a bracket. When implementing the pipework, assemblers are urged to frequently switch their attention between task and instruction, and to 'page up' or 'page down' to retrieve information from different pages.

3. *Tracking webcam:* The tracking webcam chosen is as same as that in Scenario 1. It is set with the monitor, and projected to the marker and assembling zone. The images of virtual components and real components are captured by the webcam allowing the assemblers to access live, the augmented scene identified on the monitor during assembly. By tracking the predefined markers, the customised animated guidance can be displayed on the monitor. The angle and distance between the webcam projection and the assembling zone is fixed in this instance, to ensure that the webcam is able to capture the black frame of the markers and the assembler's manipulation.

4. *Paper-based markers and components:* A large set marker and a small moveable maker are prepared with the large marker animating the assembly process from the front view and the smaller doing the same from the back. The large marker is firmly set 1.5 meters above the ground to the left of the pipe model throughout the entire assembly. This setting ensures the projection from the webcam to the marker without the constant blocking of assembly manipulation. The 'to-be-assembled' real-scale physical pipes are placed on the ground of the assembling zone, as depicted in Figure 22.

- Software Setup

The set of software used for creating the AR scene and pipe models is as same as that in Scenario 1. Models are real-time loaded during the assembly task, so that the assembler is able to control the animation process by left-clicking (loading the model and playing the animation) or right-clicking the mouse (unloading the model and reversing animation).

- Contents Creation of Virtual Assembly Animations

The piping system used consists of 13 spatially functioning pieces (Figure 23). These components are dismantled in advance and positioned in the 'work-piece stock area'.

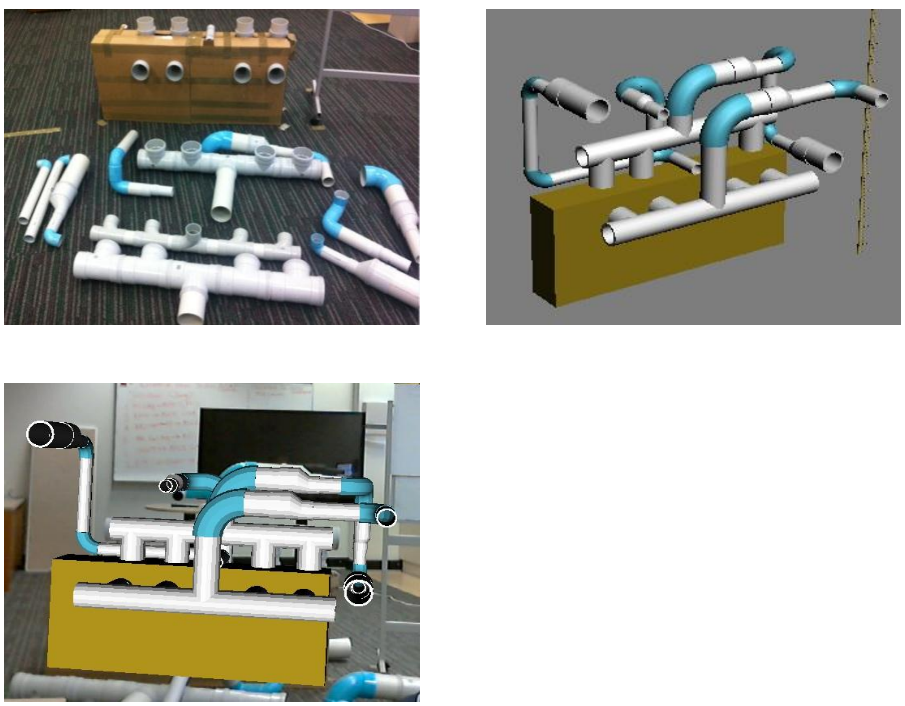


Figure 23. Panorama of 13 Components of Pipe Model in Real Environment, 3DSMAX and Animated AR System

CHAPTER 6. DATA ANALYSIS

6.1. Introduction

The evaluation of the animated AR system consisted of three parts: performance and cognitive validation, training effect validation and useability evaluation. Performance, cognitive and training effect validations are implemented through experiments designed to prove that the animated AR system is superior to conventional methods. Those in the construction assembly industry have acknowledged that current working practices are in need of substantial improvements, in terms of task guiding and training and they have identified 3D computer modelling and visualisation techniques as one way of achieving this goal. The motivation for using 3D modelling however is not evenly distributed. It was observed that while mechanical engineers have a strong motivation to use 3D modelling due to the greater volume requirements for their systems, others such as construction contractors have less motivation to go beyond 2D CAD. The result is an overall unwillingness to go to the perceived expense, in terms of both time and money, of producing designs in a 3D format. The positive findings from the experiments, if obtained, can be instructive to the construction research and industry in motivating a move toward AR applications and research. The results could also help with establishing the foundational principles related to the application of appropriate AR visualisation. The research described in this section aims to demonstrate the capability of the AR system in real assembly scenarios. To do this, two experiments were designed in which different assembly scenarios were compared with prevalent methods to validate the benefits provided by the system. The objective of experimentation is not only to answer the question, ‘Which visualisation means is more effective?’ or ‘Which can contribute to real construction practice?’, but also to explore the theoretical findings relating to human factors. For example, if certain visualisation technology in assembly guidance/training could better stimulate on-task performance, or cater for the recall and learning effect of training, how would this impact upon the cognitive endeavour and set aside more resources or effectively inhibit the rehearsal competition? Such conclusions can be reached on a universal level that could benefit other science and technology domains. Useability evaluation is also applied to identify problems in the user interface design and to suggest further improvements in interface design for the animated AR system.

6.2. Experiment I, Scenario 1: LEGO Assembly Scenario

a. Background

The LEGO assembly scenario aims to compare assembly performance and the relevant cognitive effect on the assembler under different visualisation means from a construction application related perspective. The conventional benchmark is the prevalent 3D paper-based manual, which is sometimes informally called the ‘instruction’.

b. Contrast of Alternatives

A feature comparison between 3D planar manuals and animated AR visualisation is presented in Table 7. In 3D paper-based manuals, since the information context regarding numerous assembly steps is scattered over consecutive pages due to the limited size of the paper carrier, the difficulty for information orientation is comparatively greater, and continual visual transition is almost inevitable. For instance, aside from movements like picking, comparing, grasping, rotating, connecting and fixing the to-be-assembled components typical in work-piece stock and assembling areas, the assembler must sacrifice several non-assembly-related kinetic operations to compensate for the understanding of assembly drawings/manuals, for example, paging up/down, head swivelling and comparing various elevations.

Table 7. Comparison of 3D Paper-based Manual with Animated AR Visualisation

3D Paper-based Manual	**Animated AR Visualisation**
(4) Human Spatial Cognition Ability	(5) Human Spatial Cognition Ability
(2) Nature of Interaction	(5) Nature of Interaction
(5) Mobility	(1) Mobility
(5) System Stability	(4) System Stability
(3) Cognitive Transformation	(4) Cognitive Transformation
(4) Efficiency of Annotation	(1) Efficiency of Annotation
(4) Sequential Clue	(5) Sequential Clue

c. Statement of the Problem

The assertion, in general terms, is that the benefits of AR visualisation to the assembler predominantly come from enhanced and shared spatial comprehension, and improved cognitive transformation. However, unlike Scenario 2 in experiment II, which focused on differences between 2D isometric drawings and the patterns of AR, this experiment sought to isolate the animated AR system's unique advantages by using the 3D form of components as guidance in both treatments. This experiment was designed to measure and compare both performance and cognitive differences under two treatments. The research question in Scenario 1 is *Q1:* what advantages can animated AR visualisation provide to assemblers in terms of task performance and cognitive workload, compared with 3D manual prints?

d. Hypotheses

H1: When compared to conventional 3D manual prints, the animated AR system is able to lower an assembler's cognitive workload in designated assembly tasks due to the enhanced work-piece scene (mental resources are saved).

H2: When compared to conventional 3D manual prints, the animated AR system shortens the time spent on component selection and assembly operation, and reduces the amount of assembly errors.

e. Methodology

Methods: Experimentation using major statistical methods was accompanied by three supplementary evaluation methods. One of them was to obtain quantitative performance information through observation or monitoring of the subjects' task performance during experiment. The second method was to gather qualitative rather than quantitative feedback and results from different treatments of group. Thus questionnaire was applied, which the subjects filled different types of questions from their experience in the experiment. The third method was to use the NASA task load index to measure and compare the mental load of various visualisation alternatives.

Tasks: Each group first implemented the assembly under a specific treatment, and then swapped to another treatment.

Measurement: Two types of measurements were taken: task performance and perceived mental workload. Task performance is defined as a combination of the time taken for completion and the number of errors. Mental workload was measured via the NASA task load index. Subjects rated each of the 6 categories (mental demand, physical demand, temporal demand, effort, performance, frustration level) based on their experience in the experiment, using a 20 point scale.

Experimental Variables: the following independent variables involved in the experiment were identified and determined:

- Viewing Conditions: AR vs. 3D view

- Task Element: selecting and installing the correct components based on the instructions in the 3D manual prints vs. selecting and installing the correct components on the basis of the augmented images on the animated AR system

Materials: Two sets of LEGO models from LEGO MINDSTORMS NXT 2.0 (model A and B) (see Figure 15a) and the respective 3D manual prints/AR patterns were used (see Figure 12). In this instance, relatively small models were chosen to simulate a real case of small product assembly. Small prefabricated LEGO models incorporating several shapes and colours made the experiment easy to implement, and the multiple-marker feature coded into the AR system provided the benefits of reviewing the small scale mode.

Human Subjects: Twenty eight (28) graduate students/participants (4 groups with 7 in each group) were recruited to participate in the study.

Procedure:

1) *Training session:* Before the start of the actual experiment, all the subjects familiarised themselves with the treatments. They were assigned enough time to practice the use of the different visualisation patterns.

2) *Real experiment*: The next step was the implementation of the real experiment. Various components were randomly stacked on the surface of the workbench. In both treatments, the goal of the subject groups was to assemble all components to form the final LEGO robotic structure based on their understanding of the given treatment.

3) *Post-session questionnaire*: The subjects completed the post-test questionnaires and the NASA task load index rating after the experiment. An open discussion with the experimenter was implemented as part of the experimenter's observational assessment.

f. Statistical Design

The four-group, two-period crossover design explained in the preceding discussion was structured to test the following hypothesis:

- The real model is a linear regression model; therefore all the elements in the model will have a linear relationship with the performance Y.
- The residual ε of the model is independent and normally distributed with mean 0 and variance σ. That is $\varepsilon = N(0, \sigma)$.

A major factor to be considered is the influence of treatments on the outcome of the trial. Other influencing factors include trial period, with group difference assumed to be minor factors.

On the basis of the above assumptions and in consideration of the effects of the factors mentioned above, let Y be the performance of the *k*th group at the *j*th period by the *n*th method to assemble the *g*th LEGO model. Thus the initial statistical model can be described in the following equation:

$$Y = M_{(n)} + P_{(j)} + T_{(g)} + \varepsilon \tag{6.1}$$

Where

- *Y* = the time of completing task/the number of errors for *g*th LEGO model (g=1, model A; g=2, model B) by the *n*th treatment (n=1, 2D drawing; n=2, AR) in the *k*th sequence (k=1, group1; k=2, group 2) which is administered at the *j*th period (j=1, period 1; j=2, period 2).
- *M* = the direct fixed effect for *g*th LEGO model by the *n*th treatment in the *k*th sequence which is administered at the *j*th period.

- P = the set effect of the *j*th period.
- T = the set effect of the *g*th model.
- $\varepsilon = N(0,\sigma)$, random fluctuations which are independent and normally distributed with mean 0 and variance σ.

The tool used to analyse the data was SAS.

6.2.1. Results and Discussion

The raw experimental data and the questionnaire data were collected during the experiment and then processed for further statistical analysis and interpretation. The results and discussion are presented as follows:

- Effect of Treatments on Time of Completion

Figure 24 indicates that participants in treatment two had, on average, a shorter time of completion (7.37 mins), compared with participants in treatment one (11.91 mins). An Analysis of Variance (ANOVA) was conducted on the different effects of guiding methods on the time of completion. In statistical significance testing, the p value is the probability of obtaining a test statistic at least as extreme as the one that was actually observed, assuming that the null hypothesis is true. One often 'rejects the null hypothesis' when the p value is less than 0.05. When the null hypothesis is rejected, the result is said to be statistically significant. In this experiment, the average time of completion depending on the individual guidance (manual and AR) is statistically significant, $F(1,20)=23.80$, p value<0.01. Therefore, AR does appear to have an advantage with regard to time of completion (38% time was reduced), compared with the assembly manual prints.

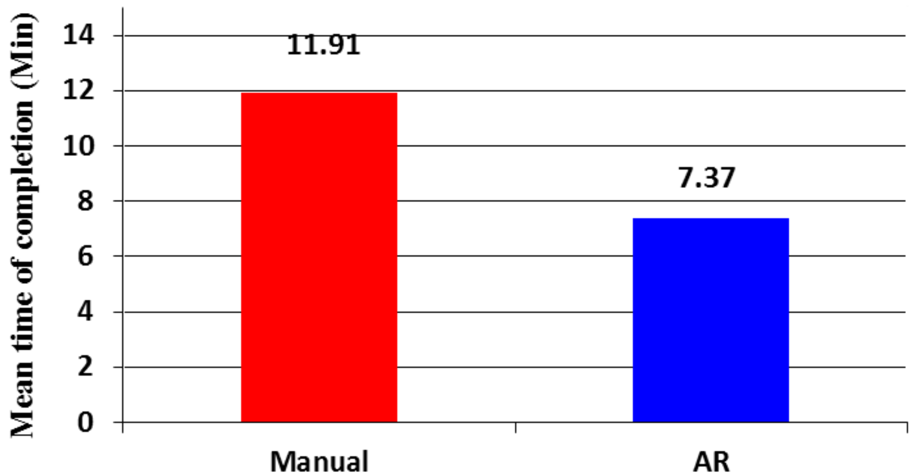


Figure 24. Average Time of Completing LEGO Assembly

Data collected from trials with the 4 groups of subjects was analysed to validate the statistical model described by Equation 6.1. Figure 25 shows the original raw data of the performance time for the crossover combinations ‘AR+Model A’, ‘AR+Model B’, ‘Manual+Model A’ and ‘Manual+Model B’. The time measurement for treatments varied considerably; all of the points in the curve of the treatment using the manual were above those of the AR treatment, illustrating that for both models the subjects using AR visualisation spent less time than those using the manual prints.

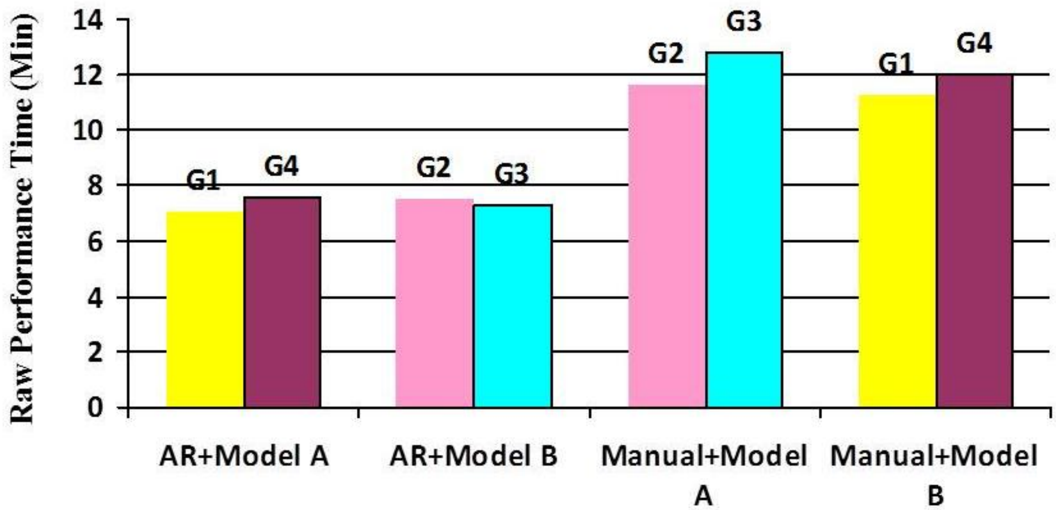


Figure 25. Raw Time Plot for Each Treatment for LEGO Assembly

The performance advantages of the AR system are discussed. Animated AR visualisation provides a dynamic demonstration of consistent information context via animation segments displayed within each assembly step. Users could detect the existing dimensions from already-positioned components as well as the virtual to-be-assembled components attached from a see-through HMD or projector. At the same time, the animation dynamically demonstrated the assembly process in HMD by approximating the virtual 'to-be-assembled' objects to the 'already-positioned' ones assembled in the ideal positions. This enabled users to mimic each assembly step and lowered the difficulty of the operation. Demonstrating a series of virtual animation segments that seamlessly integrated with the real environment, AR replenished the perceptive and cognitive vacancy caused by individual differences in the user's information retrieval capacity and lowered a certain degree of influence that the task difficulty imposed. Consequently, animated AR visualisation eased information retrieval. Offering real-time in-situ assembly guidance is another characteristic feature of the animated AR system. In each step that was observed in experiment I, the AR animation scenario dynamically and sequentially ushered the position changes of spatial components by means of the activation of each animation segment triggered by the participants themselves. When completing each animation segment, the animated AR system turned into a visual tool for presenting the statically augmented component images. In parallel, the animation was temporarily suspended for the next trigger by participants. During each suspended interval, the participants were given sufficient time to pick up the components from the rest of the to-be-assembled components, and place them into their final positions. In light of this, the assembling operations and augmented guidance proceeded together.

- Effect of Treatments on Number of Errors

Figure 26 indicates the average number of errors in accomplishing the LEGO assembly task. This chart reveals that in AR treatment, participants had a lower average error rate compared with using the manual treatment (1.30 vs. 3.40). ANOVA was conducted on the effect of guiding methods on erroneous assembly. The average number of errors depending on individual guidance (manual and AR) is statistically significant, $F(1,20)=6.60$, p value=0.02. Therefore, AR appears to have an advantage in reducing erroneous assembly (62% error reduction), compared with the 3D manual prints.

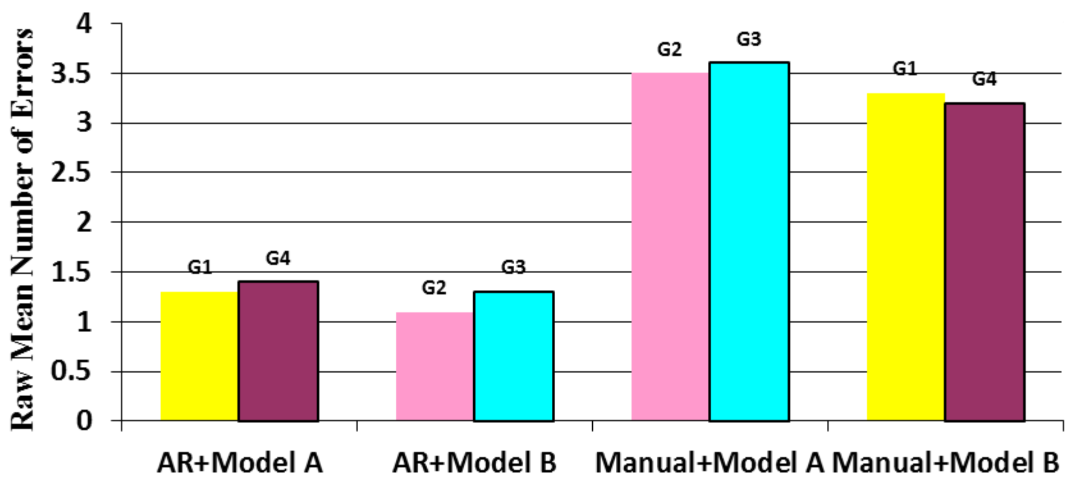


Figure 26. Raw Average Number of Errors Plot for Each Treatment for LEGO Assembly

Data collected from trials with the 4 groups of subjects was analysed to validate the statistical model described by Equation 6.1. Table 8 shows the person-time of error in crossover combinations. There were 13 steps to take to complete both LEGO models for each subject, where the 3rd, 5th, 7th and 12th steps were more difficult than the others (with step 12 being the most difficult). Using the manual (72), the person-time taken within each of these 4 steps was more than twice as much as that taken using AR (31). For the less difficult steps, such as 1st, 2nd, 4th and 13th, the person-time of error was typically larger using the manual (15) than under AR (8). Noticeably, the errors occurring within the least difficult steps (for example, the 6th, 8th, 9th and 13th step) were only found among subjects using the manual prints.

Table 8. Number of People that Erred Within Each Step for Each Treatment Combination

Step	**1st**	**2nd**	**3rd**	**4th**	**5th**	**6th**	**7th**	**8th**	**9th**	**10th**	**11th**	**12th**	**13th**
AR	*5*	*2*	*6*	*1*	*5*	*0*	*7*	*0*	*0*	*1*	*0*	*13*	*0*
Manual	*7*	*3*	*15*	*4*	*12*	*2*	*18*	*1*	*1*	*4*	*2*	*27*	*1*

The arguments to explain the performance differences are discussed. In the experiment, participants may have undergone considerable mental stress given the limited time they had in which to complete the tasks. To minimise stress, it was crucial to ensure that the information context was coherent, brief and easy to understand. In the animated AR system, it provided a dynamic demonstration of consistent information context via animation segments displayed within each assembly step. Participants could detect the existing dimensions from in-place components as well as the virtual ‘to-be-assembled’ components attached via the computer screen or projector. At the same time, the animation dynamically demonstrated the assembly process by approximating the virtual to-be-assembled objects to the in-place ones, assembled in the correct positions. This enabled the participants to mimic each assembly step and lowered the difficulty of assembly operations. Therefore the task errors were reduced. It was observed that during the experiment some participants used the manual for guidance, and they reported after the experiment that they often did not understand how to assemble certain parts due to the lack of information on the assembly path in the manual prints. With AR, however, the components dynamically moved towards their destinations so that the assembly paths could be easily viewed at hand by rotating the markers. Moreover, some participants using the 3D manual complained that it was too difficult to understand, while some even reported that it was too ‘frustrating’ to read the manual. Interestingly, some participants using the manual were so confident that they had understood the manual very well and that therefore they would not make any errors. However, errors still occurred. Therefore, it was concluded that the explanations and instructions in the assembly information manual were less efficient than those of the AR system.

- Model Analysis

While these initial indications point to the distinctions between using AR and 3D manual prints to accomplish tasks, it is important to validate the sources of the differences. The following discussion examines the effects of each factor (M, P and T) in Equation 6.1. The method applied and time period taken can be represented by factor M*P. The p value of 0.44 shows that the interaction was not presented. Therefore the interaction represented by M*P can be consider insignificant. In the case of unimportant interactions, the analysis of factor effects can proceed as for cases of no interaction, implying that one can ordinarily examine the effects of each factor separately in terms of the factor level means. This separation of factor effects is of course, much simpler than a joint analysis of the two factors based on the treatment means, which is required when the interactions are important. The hypothesis to test first was that there were no significant effects due to interaction between factors T (LEGO model) and P (Period) but that on the contrary, there were significant effects resulting from the factor M (Method). An ANOVA test was implemented for the statistical model with the data from the experiments and the results from the SAS system (illustrated in the Table 9).

Table 9. Statistical Results of Two-way ANOVA Test for LEGO Assembly

Source	**DF**	**Mean square**	**F value**	**P value**	**Significance**
Method (M)	*1*	*246.92*	*19.83*	*0.00*	*Significant*
Model (T)	*1*	*2.99*	*0.42*	*>.05*	*Insignificant*
Period (P)	*1*	*0.24*	*0.32*	*>.05*	*Insignificant*
Method*Period (M*P)	*1*	*4.66*	*0.62*	*>.05*	*Insignificant*

The probability, computed on the assumption of the insignificance of certain factors, that the test statistics would take a value as extreme or more extreme than that actually observed, is called the p value of the test. The smaller the p value, the stronger the evidence against the above assumption provided by the data. If the p value for a certain factor is less than or equal to 0.05 (%5) (industrial standard), then the factor can be considered significant; otherwise it is insignificant. Since the p values of factors T, P and M*P are all larger than 0.05, the effects of factors T, P and M*P can be considered insignificant. On the contrary, the p value of the factor M is less than 0.05, indicating that the method factor is the major, important factor. After deleting the influence of the factors P, the statistical model becomes:

$$Y = M_{(n)} + \varepsilon \tag{6.2}$$

An F-test was applied to the model equation 6.1 to further validate the simplification. The f value, as 1.85 with the corresponding p value of 0.95 demonstrated the insignificance of this simplification. Therefore, the simplification of model 6.1 down to 6.2 was supported from a statistical standpoint. A t-test was further applied to model 6.2 and yielded an estimated performance difference for these two methods, which are 4.54 minutes and 2.10 errors with p values of 0.01 and 0.02. From the final model, the conclusion can be drawn that the treatment used (*M*), has a linear relationship with the task performance (*Y*). Thus, *H2* is supported because the animated AR visualisation does appear to provide an advantage in time of completion and amount of assembly error compared with the 3D manual prints.

- Effect of Treatments on Cognitive Workload

Figure 27 indicates the mean rating of the NASA task load index. Rating results indicate that the participants in the AR treatment produced an average score of 9.84, much lower than the score of 13.64 in the manual treatment. Thus, it is believed that subjects conducting manual-based assembly underwent higher mental stress than those using

AR-based assembly. ANOVA was conducted on the different effects of guiding methods on cognitive load. The effect was statistically significant (p value=0.01). Therefore, the hypothesis that the manual appears to place a greater mental workload on the participants and that AR animation has an average effect on the lowering of the cognitive workload in the LEGO model assembly task (*H1)* is supported. The next chapter analyses the qualitative data, validating the 'enhanced work-piece scene and saved mental resources' (*H1).*

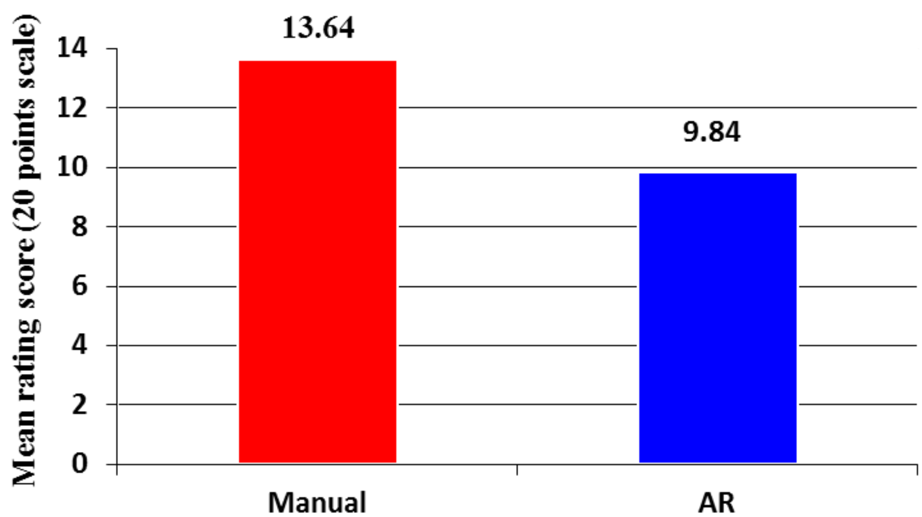


Figure 27. Plot of Average Rating Score of NASA Task Load Index Total Workload for LEGO Assembly (Higher Rating Indicates Negative Trend)

This section elaborates each category in the NASA task load index (Figure 28 and Table 10). The higher mental demand subcategory rating involved in using the manual (16.3/20 vs. 8.7/20) implies that marginally more perceptual activities such as deciding, comparing, remembering, looking and searching were required to complete the assembly task and concurrent memorising task from paper drawings. A significant difference between the two treatments was indicated by p value=0.01 and F(1,20)=2.52. In addition, trying to reason out the spatial relationship between objects via the manual may have frustrated or discouraged some of the participants, which in turn could induce greater temporal stress. These considerations can explain why the average ratings of both frustration level and temporal demand were higher when using the manual (frustration score: 14.3/20 for manual and 9.0/20 for AR; temporal score: 14/20 for manual and 11/20 for AR). Higher frustration and temporal demand levels were in accordance with the longer performance time taken when using the manual as the guidance tool. However, the 'close' performance subcategory has indicated that the subjects using the 3D manual prints were satisfied with their performance in accomplishing the task goal, an opinion equal to the subjects using AR, although this can't be explained by the higher frustration level, long performance time and more numerous errors (performance score: 7.6/20 for manual and 7.5/20 for AR; the higher the score, the more poorly the subjects thought they had performed; F=4.36; p value=0.75). The p value for physical demand was 0.00, which means there were significant differences in the physical demands of both treatments. The physical demands in using AR are less (12/20) because the participants did not consistently conduct visual transitions or movements such as 'page up/down'. This implies that the animated AR system provides a considerably natural and comfortable way of guiding assembly tasks. The effort subcategory score for AR (8.4/20) and for the manual (12.5/20) indicates that a lower overall challenge (mentally and physically) was experienced by the participants in accomplishing their level of performance, which was further confirmed by an insignificant correlation (p value=0.52).

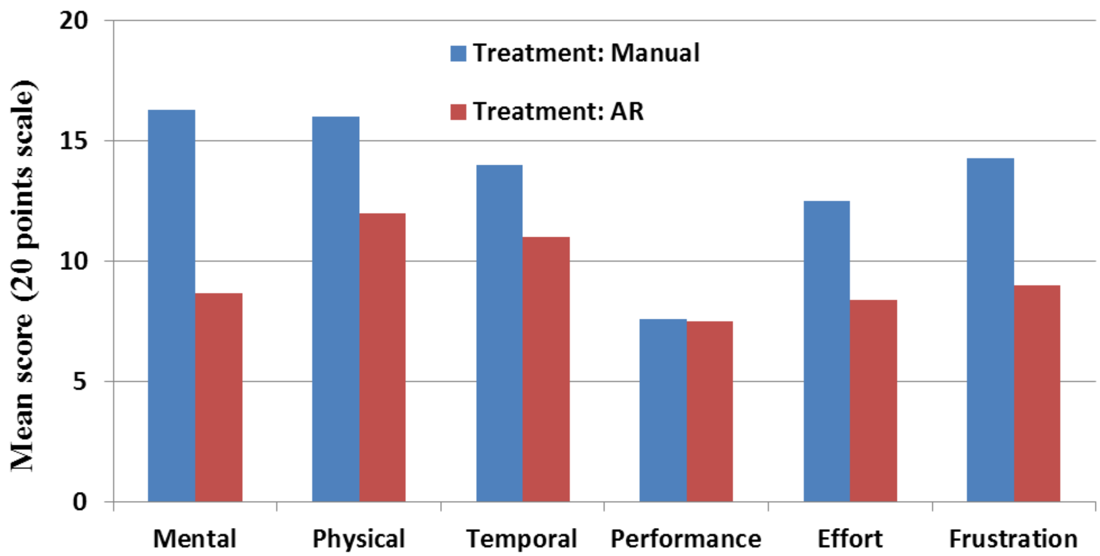


Figure 28. NASA Task Load Index Scores for Each Item for Evaluating Cognitive Workload in LEGO Assembly

Table 10. Statistical Results for Each NASA Task Load Index Rating Category for LEGO Assembly

Rating Categories	F value	P value	Significance
Mental demand	*2.52*	*0.01*	*Significant*
Physical demand	*15.62*	*0.00*	*Significant*
Temporal demand	*4.65*	*0.02*	*Significant*
Effort	*0.98*	*0.52*	*Insignificant*
Performance	*4.36*	*0.75*	*Insignificant*
Frustration level	*8.54*	*0.03*	*Significant*

- Interpretation of Questionnaire Results

A post-experiment questionnaire was designed to be completed, based on the subjects' experiences and feelings during the experiment. Two sections were included in the questionnaire. Section 1 dealt with independently rating both methods in the following nine aspects, based on a scale of 1 to 7 (Table 11). Subjects rated the quality of visual presentation of the model viewed from the animated AR system with an average value of 5.0/7.0 compared with 4.8/7.0 for 3D manual prints. The current AR model was of high resolution under TV screen/projection. This means that the quality was sufficient to avoid observation problems. Participants commented that more advanced visualisation techniques could be applied, for instance, more shading and shadow rendering to further improve the visual quality and thus enhance the user's spatial cognition. Subjects rated the mental burden of understanding the visual guidance of the animated AR system with an average value 3.5/7.0 compared with 5.4/7.0 for 3D manual prints. The lower mean score under AR visualisation indicates that the mental burden was lower. In line with the 'mental' subcategory in the NASA task load index, mental resources could be set aside, if necessary, to handle other possible cognitive interferences. Subjects rated the level of spatial awareness of the model under the animated AR system with an average value the of 5.9/7.0 compared with 3.8/7.0 for 3D manual prints, which implies that they could interact with and observe the virtual model from random angles via moving and rotating markers. This is in line with the argument of the enhanced work-piece scene in *H1*. Subjects felt much more physically comfortable using the animated AR system (4.8/7.0) than they did with 3D manual prints (3.3/7.0) as they could make direct comparisons with the augmented model under AR in order to make their selection. This was also demonstrated by the NASA task load index. A low rating for the sense of immersion in both treatments (2.8/7.0 vs. 3.8/7.0) indicates the limited sense of being presented with the visual model. However, AR has another possible trade-off; the introduction of HMD, rather than using screen/projection. Subjects identified a great deal of difference in the ease of navigation between these two treatments (3.5/7.0 vs. 6/7.0). The AR tool provided a mediated ease of navigation since the participants did not consistently conduct visual transitions or movements such as 'page up/down' in order to observe. The possibility of future use was regarded by subjects as similar for both treatments (5.4/7.0 vs. 5.8/7.0). However, subjects believed that the animated AR system was more suitable for making decisions on orientating and positioning components than 3D manual prints (4.6/7.0 vs. 5.4/7.0).

Table 11. Results and Interpretation of Questionnaire Section One for LEGO Assembly

Questions	**3D Manual Prints**	**Animated AR System**	**Interpretation**
How was the quality of visual guidance?	*4.8*	*5.0*	*The current quality of AR model is of high resolution under TV screen/projection. This means the quality is sufficient to avoid observation problems. More advanced visualisation techniques could be applied, for instance, more shading and shadow rendering to further improve the visual quality and thus enhance a user's spatial cognition.*
How was the mental burden of understanding visual guidance?	*5.4*	*3.5*	*The lower the mean score of AR visualisation, the lower the mental burden the subjects experienced. In line with the "mental" subcategory in the NASA task load index, this could reserve more mental resources for the handling, if necessary, of other cognitive interference.*
How easily did you acquire the spatial awareness of structure?	*3.8*	*5.9*	*The huge difference of two ratings can be explained as the "AUGMENTING" characteristic of the AR system. Subjects could interact with and observe the virtual model from random angles via moving and rotating markers. This is in line with the argument of the enhanced work-piece scene in H1.*
How was the physical comfort of two behaviours: AR-based comparison and the Manual-based measurement?	*3.3*	*4.8*	*Subjects felt much more physically comfortable using AR visualisation, which was also confirmed by the NASA task load index rating. They can directly compare with the augmented model in order to make a selection.*

How did you think you were involved or immersed?	*2.8*	*3.8*	*Low ratings in both columns indicate the limited sense of being presented with the visual model. A possible trade-off is in introducing HMD, rather than using screen/projection.*
How did you think when you navigated?	*3.5*	*6*	*The participants using the animated AR system did not consistently conduct visual transitions or movements like page up/down in order to observe. However, a lower rating under 3D manual prints revealed the inconvenience of navigation.*
When making decisions on orientating and positioning, how much confidence or trust did you have?	*4.6*	*5.4*	*The animated AR system was more suitable for making decisions on orientating and positioning than paper drawing, since it (AR) is more 'intuitive' and convenient to understand the paired relation between components.*
How likely would you be to keep on using this guidance?	*5.4*	*5.8*	*Both means were accepted by the participants for future use.*

Section 2 deals with the evaluation of one method against the other method in four aspects. In order to minimise the section's bias and/or order of effects in affecting the results, we counterbalanced whether the animated AR system is evaluated relative to 3D manual prints, as in questionnaire #1, or vice versa, as in questionnaire #2 (Table 12).

Table 12. Questions in Section Two for LEGO Assembly

Questionnaire #1	Questionnaire #2
Q1: I felt 3D structure presentation in the animated AR system aided understanding .	*Q1: I felt that the 3D structure presentation in the manual prints aided understanding.*
Q2: Compared with the manual prints, comparing dimensions via display of the animated AR system was more convenient.	*Q2: Compared with the animated AR system, measuring dimensions based on the manual prints was more convenient.*
Q3: The animated AR system increased the overall quality of output from the screen view.	*Q3: The manual prints increased the overall quality of output from the paper view.*
Q4: The animated AR system better facilitated the quantity of assembly work and I could complete it in a given amount of time.	*Q4: The manual prints better facilitated the quantity of assembly work and I could complete the work in a given amount of time.*
Q5: The animated AR system increased my satisfaction with the outcome of the collaboration.	*Q5: The manual prints increased my satisfaction with the outcome of the collaboration.*

Given the consistency of the questionnaire design, the data from each question statement was provided simply as four percentages, which is the actual number of respondents divided by the total number of people. In each case, the first percentage relates to 'totally agree,' and the fourth percentage relates to 'totally disagree'. For the convenience of analysing and interpreting the data from the above two questionnaires, it was rationalised that the respondents who 'totally agree' with a statement in questionnaire #1 were seen to 'totally disagree' with the corresponding question/statement in questionnaire #2. In this case, the first percentage in questionnaire #1 could be added to the last percentage in questionnaire #2. The data from the two questionnaires was collated and is visually presented in Figure 29.

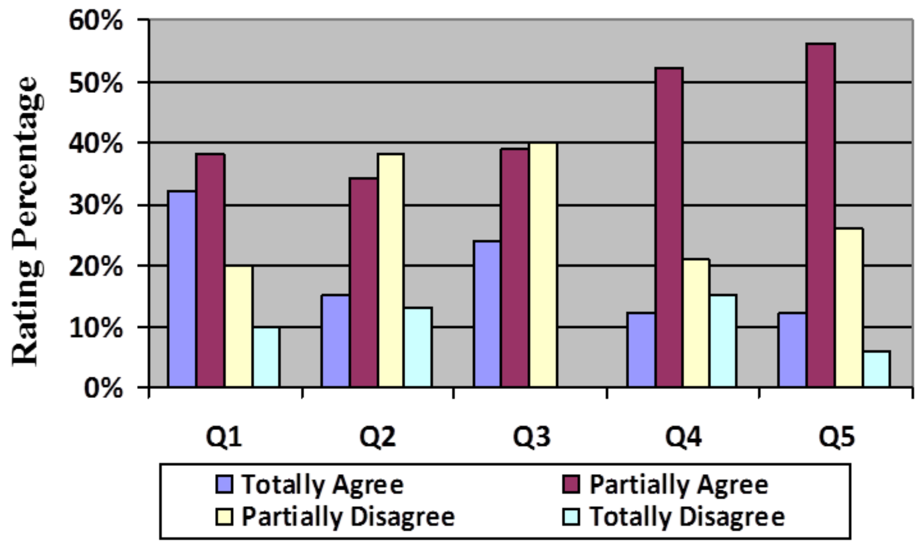


Figure 29. Plot of Responses to Questionnaire Section Two for LEGO assembly

As indicated in the plotting graph, about 70% of respondents felt that the 3D structure presentation in the animated AR system aided understanding in total or in part agreement with the statement. Question 2 asked if comparing dimensions via display on the animated AR system was more convenient and approximately 49% of respondents agreed. Half the respondents did not agree since they commented that some components were not complex enough to essentially highlight the advantage of comparing dimensions in one way, compared to another. Interestingly, respondents were still likely to maintain a positive judgment towards the advantage of comparing dimension under AR, which was confirmed by section one of the questionnaire (3.3 vs. 4.8). Most respondents (63%) believed that the AR animated system better increased the overall quality of output from the screen view, which was also in parallel with the ratings of ‘chance of keeping on using’ (5.4 vs. 5.8) in section one. The belief that the animated AR system better facilitated the quantity of work in a given amount of time and increased the quality of the user’s contribution to the project is more marked (64% vs.

36%). The belief that there was an increase in self-satisfaction from the collaboration, as a result of using the animated AR system, was well supported by 68% of the users. Based on the qualitative data from the questionnaires, the hypothesis of 'enhanced work-piece scene/saving of mental resources' (*H1*) is so far supported.

6.3. Experiment I, Scenario 2: Piping Assembly Scenario

a. Background

Although the findings from Scenario 1 have supported the cognitive and physical benefits of applying AR visualisation in small-scale assembly, the evidence that such benefits can be transferred to real-scale construction assembly instances is still undetermined, as there may exist certain differences in assembly between the two scales. For instance, the behaviour of assemblers in small-scale assembly (e.g., LEGO) is limited to hand movements only whereas the behaviour of assemblers in real-scale assembly is not limited to hand movements, as the assembler must move around the site for materials. The operational difference in these behaviours may offset the benefits of using AR. Therefore, the aim of this experiment is to investigate the pros and cons of AR in real-scale assembly, compared with 2D isometric drawings. Scenario 2 designs a real-scale piping assembly based on the experimental experience acquired from designing the LEGO small-scale model assembly. The conventional benchmark is that of commonly used 2D isometric drawings.

b. Contrast of Alternatives

A comparison of features between these two alternatives (2D isometric drawings and AR) was conducted to evaluate the specific aspects of interest. A detailed discussion is presented as follows and a summary of the comparison is given in Table 12. In this table, a rating from 1-5 (unsatisfactory to satisfactory) was given to each indicator in the evaluation. The numerical values in Table 13 represent the ratings.

Table 13. Comparison of 2D Paper-based Isometric Drawings against Animated AR Visualisation

2D Paper-based Isometric Drawings	**Animated AR Visualisation**
(2) Human Spatial Cognition Ability	*(5) Human Spatial Cognition Ability*
(1) Nature of Interaction	*(5) Nature of Interaction*
(5) Mobility	*(1) Mobility*
(5) System Stability	*(5) System Stability*
(2) Cognitive Transformation	*(4) Cognitive Transformation*
(5) Efficiency of Annotation	*(1) Efficiency of Annotation*
(1) Sequential Clue	*(5) Sequential Clue*

c. Statement of the Problem

As stated above, the general assertion is that the benefits of AR visualisation predominantly come from the enhanced and shared spatial comprehension, and improved cognitive transformation. This experiment was designed to measure and compare the performance and cognitive difference under these two treatments in the context of real-scale piping assembly. The research question in Scenario 2 is reiterated here as: what advantages can animated AR visualisation provide to assemblers in terms of task performance and cognitive workload, compared with 2D isometric drawings?

d. Hypotheses

H1: When compared to conventional 2D isometric drawings, the animated AR system is able to lower an assembler’s cognitive workload in the designated assembly tasks due to the enhanced work-piece scene (mental resources are saved).

H2: When compared to conventional 2D isometric drawings, the animated AR system shortens the time spent on component selection and assembly operation, and reduces the amount of assembly errors.

e. Methodology

Methods, Tasks, Measurement, Procedure and Statistical Design: as in Scenario 1.

Experimental Variables: the following independent variables involved in the experiment were identified and determined:

- Viewing Conditions: AR vs. 2D isometric view
- Task Element: selecting and installing proper components on the basis of instructions in 2D isometric drawings vs. selecting and installing correct components on the basis of augmented images from the animated AR system

Materials: Two sets of piping systems (model A and B) (see Figure 15b) and the respective 2D isometric drawings/AR patterns were used (see Figure 13a). In this instance, real pipe models with various shapes and dimensions were chosen to simulate real scale construction assembly. Two sets of pipe systems were designed as the same in component number and structure, containing the same number of assembly steps. The difference in the two models in terms of assembling difficulty was tested as insignificant (p value=0.74).

Human Subjects: Twenty (20) graduate students/participants (4 groups with 5 in each group) were recruited to participate in the study.

6.3.1. Results and Discussion

The raw experimental data and questionnaire data were collected during the experiment and then processed for further statistical analysis and interpretation. The results and discussion were presented as follows:

- Effects of Treatments on Time of Completion

Figure 30 indicated that participants in treatment two completed the tasks, on average, in half of the time (16.30 mins), compared to participants in treatment one (34.30 mins). ANOVA was conducted on the different effects of the guiding methods on the time of completion. In statistical significance testing, the average time of completion depending on the type of guidance (drawings and AR) is statistically significant, F(1,16)=37.23, p value=0.00. Therefore, AR does appear to have an advantage in time of completion (time was reduced by 50%), compared with assembly manual prints.

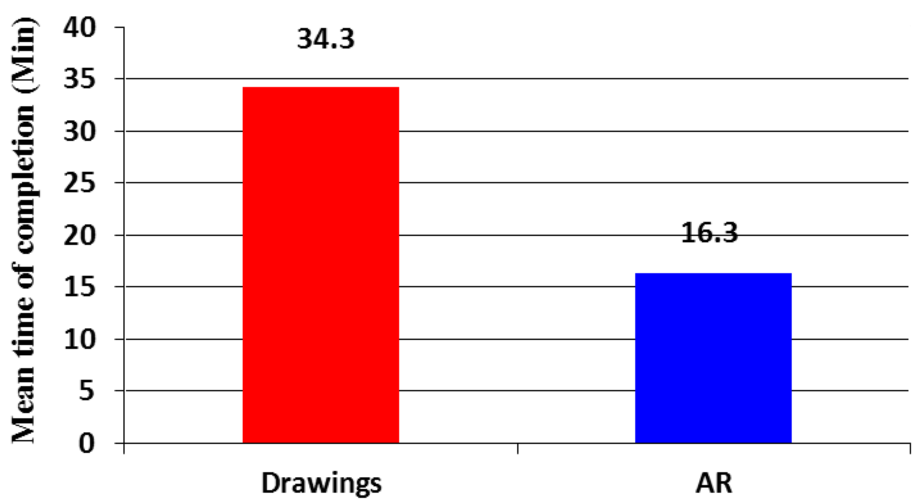


Figure 30. Average Time of Completion for Piping Assembly

Data collected from trials with the 4 groups of subjects was analysed to validate the statistical model described by Equation 6.1 (but without $T_{(g)}$). Figure 31 shows the original raw data of the performance time for crossover combinations ‘AR+Model A’, ‘AR+Model B’, ‘Drawings+Model A’ and ‘Drawings+Model B’. All of the points in the curve of treatment drawings are above those of treatment AR, which indicates a significant decrease in task completion time when using AR visualisation.

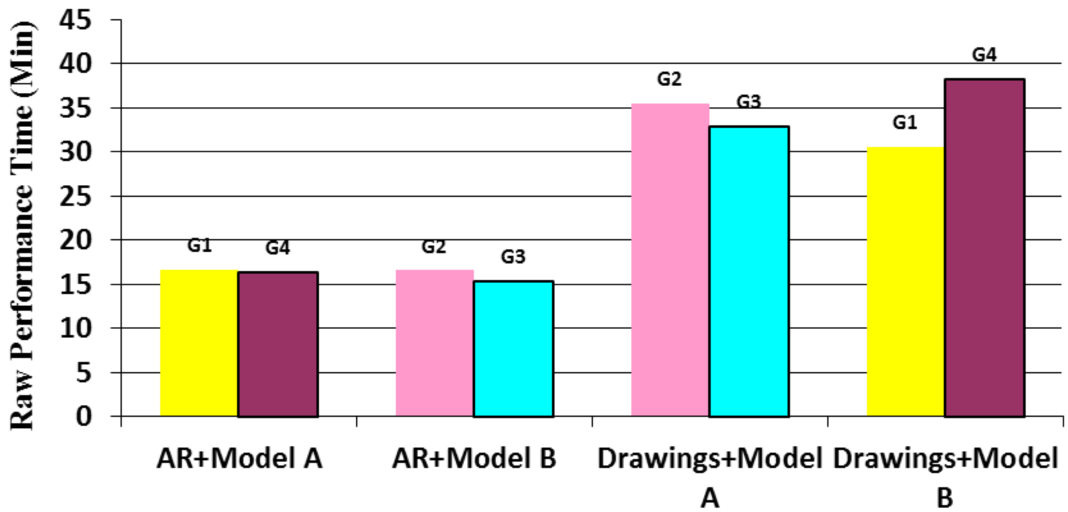


Figure 31. Raw Time Plot for Each Treatment for Piping Assembly

It is observed that the participants from the group using drawings spent a large amount of time in reading and understanding drawings before they could conduct the actual assembly. Even during assembly, they frequently suspended assembly behaviour and referred back to the drawings to reconfirm the current or previous assembly steps. In comparison, as observed in AR groups, the participants were more confident about their judgments regarding parts selection and installation, and were therefore able to complete each assembly step in a shorter time with AR.

- Effect of Treatments on Number of Errors

Figure 32 indicates the average number of overall errors in accomplishing the piping assembly task. This chart reveals that in the AR treatment, participants halved the number of overall errors compared with the drawings treatment (2.5 vs. 5). Figure 34 presents the original raw data of the mean error under each group. All of the points in the curve of treatment drawings are above those of treatment AR, which indicates a significant decrease in task error when using the AR visualisation. ANOVA was conducted on the effect of guiding methods on erroneous assembly. The average number of errors depending on the individual guidance (manual and AR) is statistically significant, $F(1, 16)=8.40$, p value<0.01. Therefore, AR appears to have an advantage in reducing assembly error (50% of errors were reduced), compared with isometric drawings.

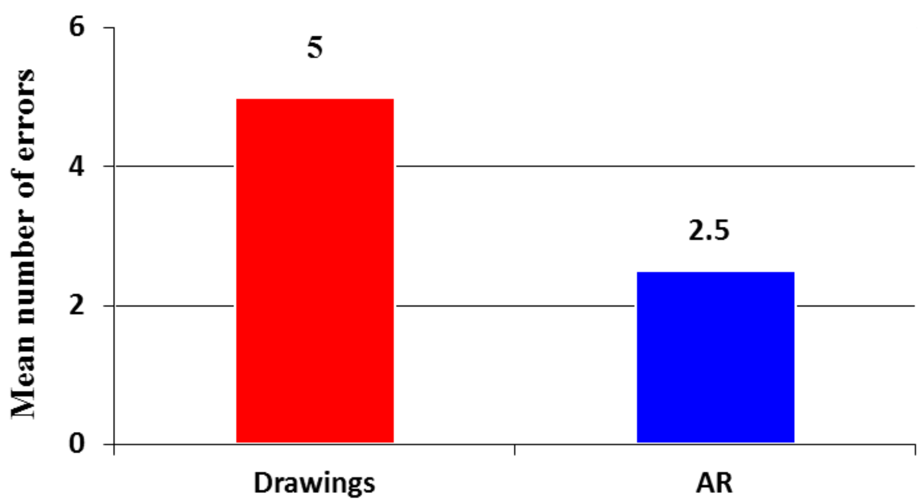


Figure 32. Average Number of Overall Errors in Piping Assembly

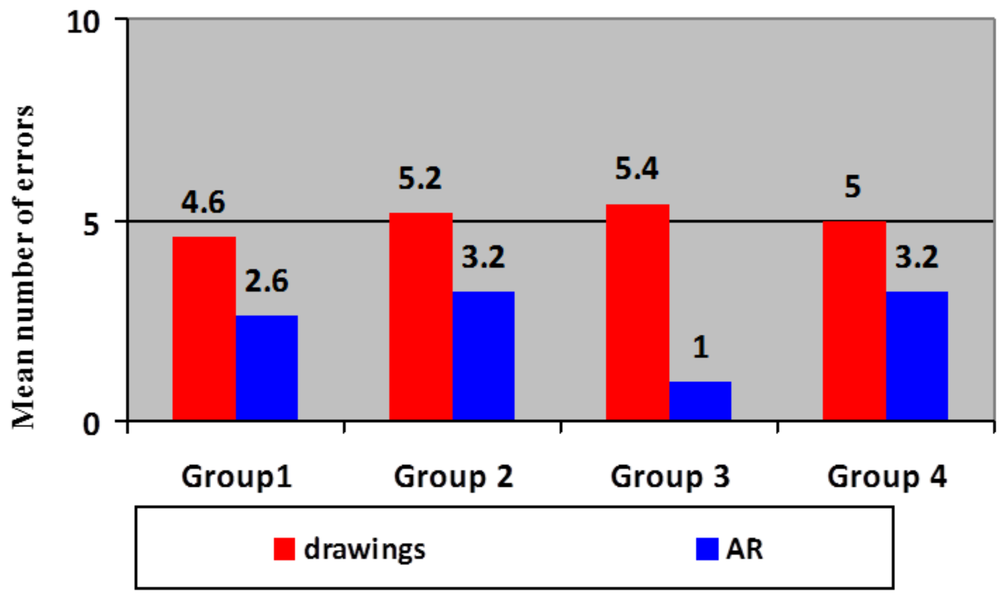


Figure 33. Raw Error Plot for Each Treatment for Piping Assembly

Table 13 indicates the statistical number of errors in each category. In the drawings-guided assembly totals for all the human subjects, 101 errors consisted of 43 pipe selection errors and 58 pipe installation errors. 34 out of 43 pipe selection errors, led to installation errors, whereas 24 out of 58 installation errors were due to orientational or positional mistakes. In the AR guided assembly, 50 overall errors comprised 25 pipe selection errors and 25 pipe installation errors. 20 pipe installation errors resulted from 20 incorrect pipe selection errors, while 5 incorrect pipe installations were due to orientational or positional mistakes. It is indicated that the participants, despite committing numerous selection errors (43 errors), were prone to err when they used isometric drawings to install the pipes (58 errors), but they were also equally likely to err in two instances when using AR (25 vs. 25). In Table 14, the selection error falls into two error categories: *error until step assembly starts* and *error before step assembly* *starts.* The former indicates that participants did not notice that they had chosen the wrong pipes after they had assembled them, while the latter indicates that participants did not notice that the wrong pipes had been chosen until they were about to begin the assembly. Statistics under both categories show that nearly double the number of mistakes was made for participants using drawings compared with AR (34 in drawings vs. 20 in AR; 9 in drawings vs. 5 in AR). It also indicated that in addition to the average reduction of error in each category, AR significantly reduced the occurrence of such errors committed in determining pipe orientation and position (5 in AR vs. 24 in drawings).

Table 14. Comparison of Number of Errors into Each Category of Isometric Drawings against Animated AR Visualisation

	Overall Error	**Selection Error**		**Installation Error**	
		until step assembly starts	**before step assembly starts**	**due to incorrect selection**	**due to orientation or position**
Drawings	*101*	*34*	*9*	*34*	*24*
AR	*50*	*20*	*5*	*20*	*5*

In order to investigate the occurrence of error under the two treatments when varying the assembly difficulty, a comparatively high level of difficulty was assigned to specific pipes. For example, with Model A, a pair of pipes named P14A15-1-No.3 and P14A27-1-No.2, and P14A15-1-No.1 and R14A73-1-No.1 are similar in shape but different in length (Figure 34a); with Model B, a pair of pipes named P1-No.1 and P3-No.1 were different in shape (component direction) but similar in length, while a pair of pipes named P4-No.1 and P3-No.4 were different in length but similar in shape (Figure 34b).

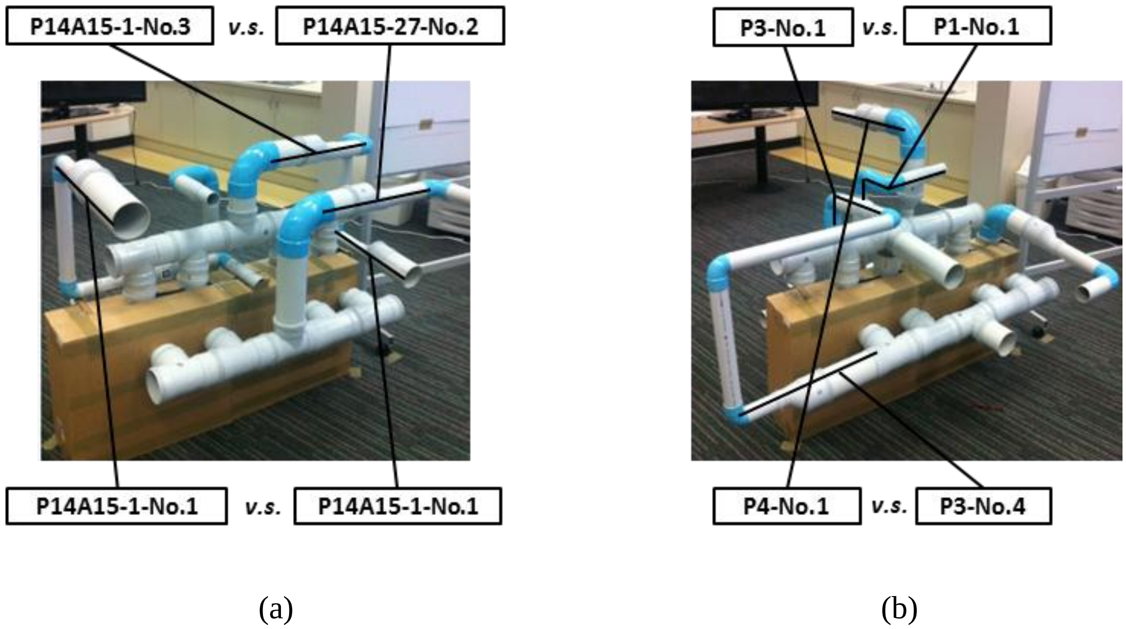


Figure 34. Higher Assembly Difficulty Devised for Investigation of Occurrence of Error

Table 15 counts the number of overall errors in terms of selection between these similar items. There were no distinct differences in error when the participants applied the respective treatment to select and install the pipes that were similar in shape but slightly different in length (Model A: 5 vs. 6; 6 vs. 6; Model B: 3 vs. 4), whereas significant differences in error occurred between P1-No.1 and P3-No.1, which are similar in length but different in shape. This indicates that when judging shape, the participants under the AR treatment were not prone to err (AR: 2). However, a large number of errors were committed under the drawings treatment (Drawings: 11). In addition, the judgment on pipe shape relative to size, reduced the performance of participants especially under the drawings treatment, which can be found in 11 vs. 4 (both for Model B).

The arguments to explain the performance difference are discussed as follows: using a ruler to measure the length of pipe based on the scale in isometric drawings is generally not likely to cause error. As can be learned from drawings treatment, the few occurring errors were mainly due to human mistakes, such as reading a label incorrectly in drawings or making a simple measurement mistake. Unlike isometric drawings, AR augments a scene where the participants can judge pipe thickness, diameter, shape and length with an immediate comparison between virtual and real items (see Figure 22). Errors occurring under AR treatment were generally due to the virtual items being not precise enough to be superimposed upon the physical counterparts or because the differences in pipe shape were unconsciously ignored or not perceived by the users. As for shape judgment, the advantages of AR appear in the accuracy of discerning the specific shape and understanding the versatile structure of pipes; it is more difficult to make a mistake in the AR scenario. The same contents, on the contrary, were not easy to comprehend for the ordinary user lacking isometric knowledge. Consequently, some of the users under the drawings treatment had committed errors of selection between P1-No.1 and P3-No.1.

Table 15. Number of Errors Due to Incorrect Selection

Model A		
Pipe ID	P14A15-1-No.3 vs. P14A27-1-No.2 (similar: shape; different: length)	P14A15-1-No.1 vs. R14A73-1-No.1 (similar: shape; different: length)
AR	*5*	*6*
Drawings	*6*	*6*
Model B		
Pipe ID	P1-No.1 vs. P3-No.1 (similar: length; different: shape)	P4-No.1 vs. P3-No.4. (similar: shape; different: length)
AR	*2*	*3*
Drawings	*11*	*4*

- Rework and Cost Analysis

Time spent on work is the first factor that impacts upon assembly cost. The more time consumed, the higher the wages that should be paid to assemblers. The following charts represent the composition of the average time of completion for the piping assembly under the two treatments (Figure 35). The two treatments cannot significantly alter the proportion of rework time/original time in total time (rework times are 39% vs. 35%, as indicated by the sections of green, purple and light blue; original times are 61% vs. 65%, as indicated by the sections of blue and red). However, AR can significantly shorten either the original time or the rework time. When switching to AR, assemblers spent an average of half the rework time that was consumed under isometric drawings, to correct assembly errors (6.30 mins vs. 11.70 mins) or even less to complete the original assembly task (10.00 mins vs. 22.20 mins). In other words, the reduction of time due to switching treatment implies that AR facilitates an assembler's understanding of the assembly process. As opposed to the conventional measuring by scale on drawings, the unique approach of identifying the to-be-assembled components under AR is much faster. Although the proportion of time spent on pure assembly operations varied a lot, from 12% under AR to 6% under drawings, the value was still 2 minutes for both treatments. Little change was also found in the indicators of dismantling time and reassembling time, which were only relevant to assembly operations rather than in interactions with treatments. Therefore, when considering the indicators of time, costs incurred by payment (payment for work on original and rework phases) under isometric drawings are 2.1 times that of those under AR (16.30 mins wages vs. 34.30 mins wages) (assuming the same rate of pay for original time and rework time).

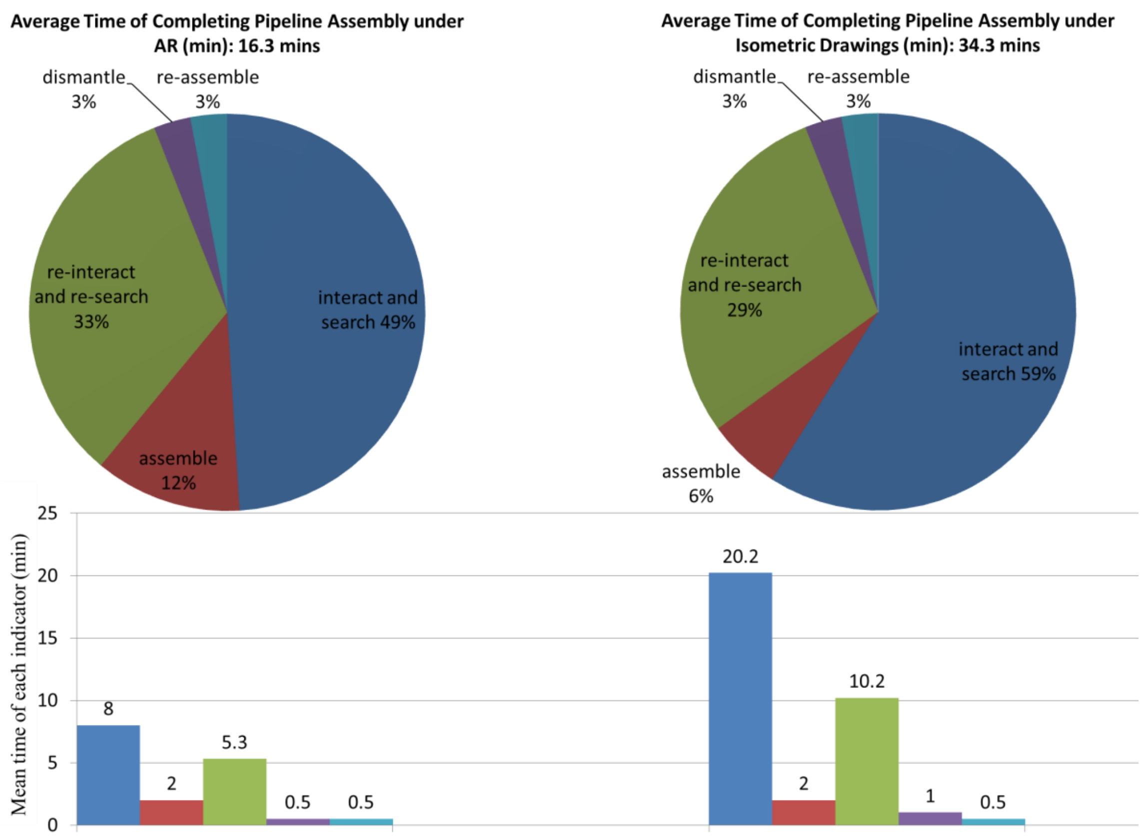


Figure 35. Individual Time Indicator Relative to Average Overall Time under Each Treatment (left: AR; right: isometric drawings)

Besides the cost of payment, rework (such as correcting erroneous assembly) incurs other additional costs. When incorrect pipes are installed or the correct pipes are incorrectly installed, assemblers need to correct the error by removing the appropriate pipes and re-welding new pipes. If the erroneous assembly occurs in the final assembly, one instance of dismantling, as well as a re-welding of the correct pipe (both for one end only) needs to be conducted. In other cases, two instances of dismantling and re-welding are needed (one pipe has two ends). As discussed previously, the cost of payment for work on original and rework phases is the cost incurred by re-welding the correct pipes, dismantling the incorrect pipes, and the reinstallation. In the experimental design, it is assumed that all dismantled pipes can be reused. Thus the ratio for the re-welding cost under the two treatments can be described as Equation 6.3:

$$Re\text{-}welding\,CostRatio = \frac{Re\text{-}welding\,Length(AR)}{Re\text{-}welding\,Length(Drawings)} = \frac{\sum C_{(i)} \times N_{(i)}}{\sum C_{(j)} \times N_{(j)}} \qquad (6.3)$$

where

- C = the circumference of to-be-welded pipe end.
- N = the number of dismantled (welded) pipes; the *ith* or *j*th pipe.
- i represents Model A, i = 1, P14A06-1-No.3; i = 2, P14A06-1-No.2; etc.
- j represents Model B, j = 1, P1-No.3; j = 2, P1-No.2; etc.

The overall re-welding lengths required (by 20 participants with each participant using Model A and B respectively) by calculating the statistics using Table 16, are 27675 mm for drawings and 9324 mm for AR. Therefore, the value of the *Re-welding Cost Ratio* is equal to 27675/9324=3, which indicates that measured against AR, triple the cost would be required to conduct rework on the erroneous assembly when using isometric drawings (2/3 cost on rework was saved with AR).

Table 16. Statistics for Each Factor in Equation 6.3 (20 participants conducted 40 times of assembly in total)

i (j)	**C (mm) Circumference per Dismantling**	**N(AR) No. of Dismantling**	**N(drawings) No. of Dismantling**
P14A06-1-No.3	*204*		*4*
P14A06-1-No.2	*204*		*1*
P14A06-1-No.1	*204*	*3*	*3*
P14A15-1-No.5	*314*		*5*

P14A15-1-No.4	*314*		*1*
P14A15-1-No.3	*314, 204*		*2, 2*
P14A15-1-No.2	*204, 157*		*2, 1*
P14A15-1-No.1	*157*	*1*	*2*
P14A27-1-No.4	*314*		
P14A27-1-No.3	*314*		
P14A27-1-No.2	*314, 204*	*1, 1*	*1, 1*
P14A27-1-No.1	*204*	*4*	*4*
R14A73-1-No.3	*157*		*3*
R14A73-1-No.2	*157*	*2*	*8*
R14A73-1-No.1	*157*	*3*	*1*
P1-No.3	*204*	*14*	*14*
P1-No.2	*204*		*2*
P1-No.1	*204*		*7*
P2-No.1	*314*	*8*	*28*
P3-No.5	*314*		
P3-No.4	*314, 157*	*2, 2*	*2, 2*
P3-No.3	*157*	*3*	*3*
P3-No.2	*157*	*1*	
P3-No.1	*157*		*3*
P4-No.3	*157, 314*		*2, 2*
P4-No.2	*314*	*1*	*5*
P4-No.1	*314*		
P5-No.3	*314*		*2*
P5-No.2	*314, 204*		*1, 1*
P5-No.1	*204*		

- Model Analysis

An ANOVA test was implemented for the statistical model with the data from the experiments and the results from the SAS system illustrated in the Table 17. The method applied and time period used can be represented by factor M*P, as with Scenario 1. The interaction represented by M*P can be considered insignificant as the p value is 0.31. In the case of unimportant interactions, the analysis of factor effects can proceed as would be the case with no interaction, implying that one can ordinarily examine the effects of each factor separately in terms of the factor level means. Since the p value of factor P is larger than 0.05, the effects of factors P can be considered insignificant. The p value of the factor M is less than 0.05, indicating that the method factor is the major, important factor. An F-test validates this simplification (F=1.87; p value=0.50). Therefore, the statistical model becomes:

$$Y = M_{(n)} + \varepsilon \quad (6.4)$$

This model also concludes that the treatment used (*M*) has a linear relationship with the task performance (*Y*). Thus, *H2* is supported because the animated AR visualisation does appear to provide an advantage in time of completion and amount of assembly error compared with the isometric drawings.

Table 17. Statistical Results of Two-way ANOVA Test for Piping Assembly

Source	DF	Mean square	F value	P value	Significance
Method (M)	*1*	*184.55*	*15.91*	*0.00*	*Significant*
Period (P)	*1*	*1.56*	*0.38*	*>.05*	*Insignificant*
Method*Period (M*P)	*1*	*0.53*	*3.68*	*>.05*	*Insignificant*

- Effect of Treatments on Cognitive Workload

Figure 36 indicates the mean rating of the NASA task load index. Rating results indicate that the participants in AR treatment gave an average score of 9.28, much lower than the score of 12.97 in the print manual treatment. Thus, it is believed that subjects conducting drawings-based assembly underwent higher mental stress than AR-based subjects. ANOVA was conducted on the different effects of guiding methods on cognitive load. The effect was statistically significant (p value=0.00). Therefore, the hypothesis that isometric drawings appear to place a greater mental workload on the participants, and that AR animation has an average effect in lessening the cognitive workload of the user undertaking piping assembly tasks (*H1)* is supported. The next chapter analyses the qualitative data, validating the ‘enhanced work-piece scene’ and ‘saved mental resources’ (*H1).*

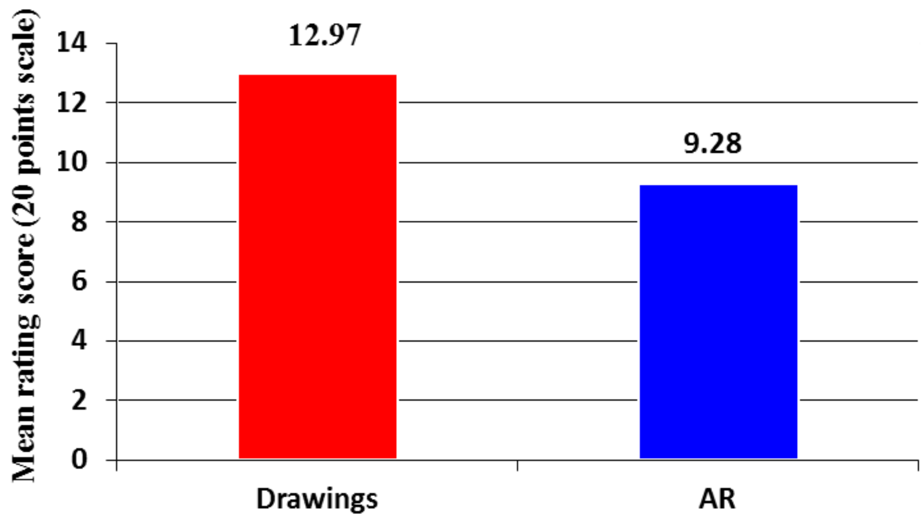


Figure 36. Plot of Average Rating Score of NASA Task Load Index Total Workload for Piping Assembly (Higher Rating Indicates Negative Trend)

This section elaborates each category in the NASA task load index (Figure 37 and Table 18). The higher mental demand subcategory rating involved in using the isometric drawings (15.8/20 vs. 6.7/20) implies that marginally more perceptual activities such as looking, comprehending, searching, remembering and deciding were required to complete the assembly task. A significant difference between two treatments was indicated by p value=0.00 and F(1,26)=65.02. However, trying to reason the spatial relationships of objects via the isometric view may not have frustrated or discouraged the participants, since the differences in temporal stress (10.9/20 vs. 9.7/20) were not significantly indicated by p value=0.49. This consideration can be explained as with the launching of the task, that participants may not have felt pressured by being given a time limit, despite being told prior to commencement, to complete the task as quickly as possible. The average rating of frustration level was higher where drawings were used (12.3/20 vs. 9.0/20; p value=0.04), which was in accordance with the longer performance time and more numerous errors when using drawings as the guidance tool. However, the close performance subcategory has indicated that the subjects using the isometric drawings were satisfied with their performance in accomplishing the task goal, equal to the subjects using AR (13.4/20 vs. 10.7/20; p value=0.16). The higher mean performance score indicates that some of the participants thought they had performed poorly after isometric drawings. However, others were confident about their performance since they felt that no mistake would be made once they had understood the drawings. The p value for physical demand is 0.026, which means there were significant differences in the physical demands for both treatments. The physical demand in using AR is lower (9.5/20 vs. 12.8/20) as the participants did not consistently conduct visual transitions or movements such as ‘page up/down’. This implies that the animated AR system provides a considerably natural and comfortable way of guiding assembly tasks. The effort subcategory score for AR (7.5/20) and for isometric drawings (15.2/20) indicates that a lower overall challenge (mentally and physically) was experienced by the participants in accomplishing their level of performance, which was further confirmed by a significant correlation (p value=0.00).

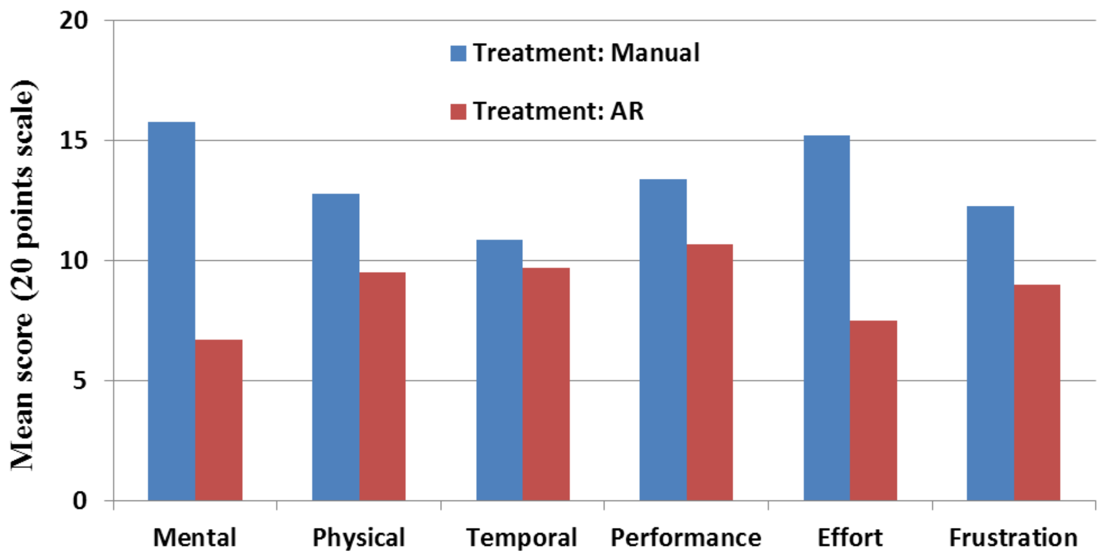


Figure 37. NASA Task Load Index Scores for Each Item for Evaluating Cognitive Workload in Piping Assembly

Table 18. Statistical Results for Each NASA Task Load Index Rating Category for Piping Assembly

Rating Categories	F value	P value	Significance
Mental demand	*65.02*	*0.00*	*Significant*
Physical demand	*5.63*	*0.03*	*Significant*
Temporal demand	*0.51*	*0.49*	*Insignificant*
Effort	*28.18*	*.0.00*	*Significant*
Performance	*2.14*	*0.16*	*Insignificant*
Frustration level	*3.59*	*0.04*	*Significant*

- Interpretation of Questionnaire Results

The questionnaire was completed based on the subjects' experiences and feelings during the experiment (Table 19). Subjects rated the quality of the visual presentation of the model, viewed from the animated AR system, with an average value of 5.7/7.0 compared with 3.2/7.0 for isometric drawings. The current AR model is of high resolution under TV screen/projection. This illustrates that the quality is sufficient to avoid observation problems. Participants commented that more advanced visualisation techniques could be applied, for instance more shading and shadow rendering to further improve the visual quality and thus enhance the user's spatial cognition. Subjects rated the mental burden of understanding visual guidance for the animated AR system with an average value of 2.7/7.0 compared with 5/7.0 for isometric drawings. The lower mean score under AR visualisation indicates that the mental burden was lower. In line with the 'mental' subcategory in the NASA task load index, this could set aside more usable mental resources for coping with any other cognitive interference, if necessary. Subjects rated the level of spatial awareness of the model under the animated AR system with an average value 5.5/7.0 compared with 2.2/7.0 for isometric drawings, which implies that they could interact with and observe the virtual model from random angles via moving and rotating markers. This is in line with the argument of the enhanced work-piece scene in *H1*. Subjects felt much more physically comfortable using the animated AR system (4.8/7.0) than using isometric drawings (3.7/7.0) as they could make direct comparisons with the augmented model under AR in order to make their selection. This was also demonstrated by the NASA task load index. However, this difference is not a great one, which implies that measuring the length based on scale was also accepted by most of the subjects. Close ratings showed in the results regarding the sense of immersion for both treatments (4.3/7.0 vs. 4.4/7.0) which indicates the acceptance of being presented with the visual model. The subjects claimed after using isometric drawings that they needed to become more 'involved' to understand the contents of the drawings. However, AR has another possible trade-off with the introduction of HMD, rather than screen/projection. Subjects identified great differences in the ease of navigation between these two treatments (2.9/7.0 vs. 5.2/7.0), implying ease of navigation with AR. With regard to the possibility of future use, the subjects were 'more willing to use AR' (6.3/7.0 vs. 3.1/7.0). All subjects were willing to attempt use of this novel technology in future assembly.

Table 19. Results and Interpretation of Questionnaire Section One for Piping Assembly

Questions	Isometric Drawings	Animated AR System	Interpretation
How was the quality of visual guidance?	*3.2*	*5.7*	*The current quality of the AR model is of high resolution under TV screen/projection. This quality is sufficient to avoid observation problems. More advanced visualisation techniques could be applied, for instance, more shading and shadow rendering to further improve the visual quality and thus enhance spatial cognition.*
How was the mental burden of understanding visual guidance?	*5.0*	*2.7*	*The lower the mean score of AR visualisation, the lower the mental burden on the subjects. In line with the "mental" subcategory in the NASA task load index, more mental resources could be saved to handle other cognitive interference, if necessary.*
How easily did you acquire the spatial awareness of structure?	*2.2*	*5.5*	*The huge difference in the two ratings can be explained as the "AUGMENTING" characteristic of the AR system. Subjects could interact with and observe the virtual model from random angles via moving viewpoints and rotating markers. This is in line with the argument of an enhanced work-piece scene in H1.*
How was the physical comfort of two behaviours: AR-based length comparison and drawing-based measurement?	*3.7*	*4.8*	*Subjects felt much more physically comfortable using AR visualisation, which was also confirmed by the NASA task load index rating. They can make direct comparisons with the augmented model in order to make their selection. However, this difference is not great, which implies that measuring the length based on scale was also accepted by most of the subjects.*

How did you think you were involved or immersed?	*4.3*	*4.4*	*Both columns are beyond the borderline (4), which indicates the acceptable sense of being presented with the visual model under both treatments. Subjects after isometric drawings claimed that they needed to 'involve' themselves more in order to understand the drawing contents.*
How did you think when you navigated?	*2.9*	*5.2*	*The participants using the animated AR system did not consistently conduct visual transitions or movements like 'page up/down' in order to observe. However, lower ratings under isometric drawings revealed the inconvenience of navigation.*
When making decisions on orientating and positioning, how much confidence or trust did you have?	*3.8*	*5.8*	*The animated AR system was more suitable for making decisions on orientating and positioning than the paper drawings, since it is more intuitive and convenient to understand the paired relations between components.*
How likely would you keep on using this guidance?	*3.1*	*6.3*	*A high score in the AR column indicates that subjects were fully willing to attempt this novel technology for future assembly instances. All subjects expressed their willingness to keep on using AR.*

Section 2 deals with the evaluation of one method against the other method in four aspects. In order to minimise the section's bias and/or to order effects to affect the results, we counterbalanced whether the animated AR system is evaluated relative to isometric drawings, as in questionnaire #1, or vice versa as in questionnaire #2 (Table 20).

Table 20. Questions in Section Two for Piping Assembly

Questionnaire #1	Questionnaire #2
Q1: I felt that the 3D pipe structure presentation in the animated AR system aided understanding.	*Q1: I felt that the isometric pipe structure presentation in drawings aided understanding.*
Q2: Compared with drawings, comparing pipe dimension via display of the animated AR system was more convenient.	*Q2: Compared with the animated AR system, measuring the pipe based on scaled drawings was more convenient.*
Q3: The animated AR system increased the overall quality of output from the screen view.	*Q3: The drawings increased the overall quality of output from the paper view.*
Q4: The animated AR system better facilitated the quantity of assembly work and I could complete it in a given amount of time.	*Q4: The isometric drawings better facilitated the quantity of assembly work and I could complete it in a given amount of time.*
Q5: The animated AR system increased my satisfaction with the outcome of the collaboration.	*Q5: The isometric drawings increased my satisfaction with the outcome of the collaboration.*

Given the consistency of the questionnaire design, the data from each question statement was provided simply as four percentages, which is the actual number of respondents divided by total number of people. In each case, the first percentage relates to ‘totally agree,’ and the fourth percentage relates to ‘totally disagree’. For the convenience of analysing and interpreting the data from the above two questionnaires, it was rationalised that the respondents who ‘totally agree’ with the statement in questionnaire #1 were regarded to ‘totally disagree’ with the corresponding question in questionnaire #2. In this case, the first percentage in questionnaire #1 could be added to the last percentage in questionnaire #2. The data from the two questionnaires was collated and is visually presented in Figure 38.

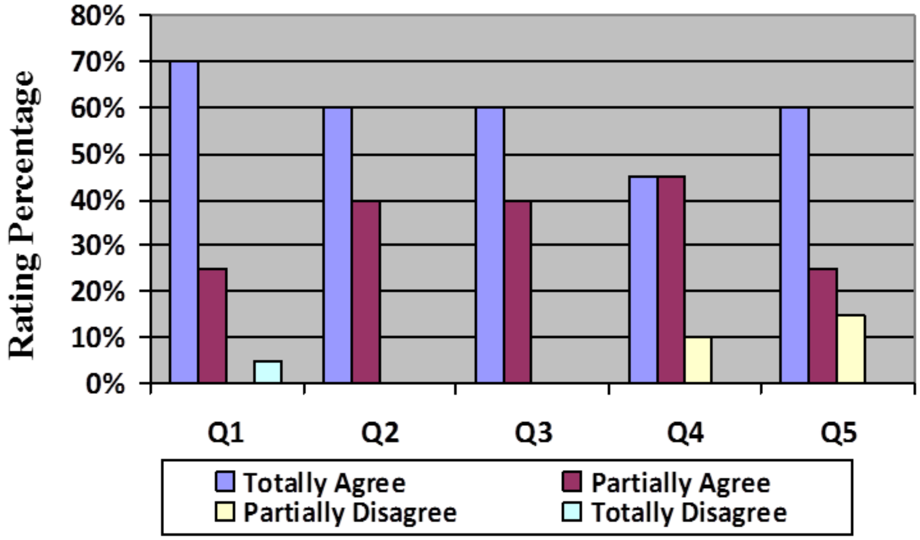


Figure 38. Plot of Responses to Questionnaire Section Two for Piping Assembly

As indicated in the plot, nearly all respondents (95%) felt that 3D structure presentation in the animated AR system aided understanding in total or partial agreement with the statement. Question 2 asked if comparing dimension via display of animated AR system is more convenient, with which all respondents agreed. The respondents were likely to maintain the positive judgment towards the advantage of comparing dimension under AR, which was confirmed by the section one of the questionnaire (3.7 vs. 4.8). All of respondents believed that the AR animated system better increased the overall quality of output from the screen view. The belief that the animated AR system better facilitated the quantity of work in a given amount of time and increased the quality of the user's contribution to the project is more marked (90% vs. 10%). The belief that there has been an increase in self-satisfaction from the collaboration as a result of using the animated AR system was well supported by 85% of the users. Based on the qualitative data from questionnaire, the hypothesis of 'enhanced work-piece scene/saved mental resources' (*H1*) is so far supported.

6.4. Experiment II, Scenario 3: LEGO Assembly Training Scenario

a. Statement if the Problem

This experiment was conducted to study the learning curves of human subjects with two assembly treatments, namely 3D assembly manuals and AR. The evidence of a learning curve in this experiment was reflected by the assembly performance. There are two independent variables which were selected for investigation: training schemes and gender differences. The research question which this experimental scenario is concerned with is: could training with animated AR visualisation contribute to faster learning, compared with training with 3D manuals? Do gender differences have any bearing on the comparative results of the two training schemes? What are the possible reasons for any differences in training or gender?

b. Hypotheses

H3: Using the animated AR system as a training tool shortens the learning curve of trainees (they learn faster) in cognition-demanding assembly. This is based on a sub-hypothesis that training within an AR environment facilitates longer WM capacity, when compared with training with 3D manual prints.

c. Methodology

Methods: Controlled experiments were the major quantitative research methods uses. The qualitative performance information was gathered through direct observation and monitoring of the subjects' task performance during the experiment.

Tasks: Each group first implemented their assembly training with a specific treatment. The test trainees were required to remember the assembly sequence and component fixation/installation, and then assemble the same model without being allowed to seek any help from the manual prints or AR.

Measurement: Task performance was videotaped and measured in terms of the factors indicated in the section 5.5.1.

Experimental Variables: the following independent variables involved in the experiment were identified and determined:

- Training Schemes: AR vs. 3D manual prints
- Gender: male vs. female

Materials: One set of LEGO model from LEGO MINDSTORMS NXT 2.0 (model A), the respective 3D manual prints and AR representation were used.

Human Subjects: Twenty eight (28) graduate students/participants (2 groups with 7 male and 7 female assemblers in each group) were recruited to participate in the study.

Procedure:

1) *Training session:* The two groups of test trainees were required to remember the assembly sequence and component fixation/installation within the specified training scheme but limited to one single LEGO model assembly cycle.

2) *Before the start of the actual experiment*: All the trainees were distracted for 5 minutes with reading materials irrelevant to the experiment, such as newspapers.

3) *Real experiment*: The two test groups of 28 students were then initiated into the first trial, one group without manual and one group without the assistance of AR. An allowance was made for further trials, if deemed necessary.

d. Statistical Design

The between-subject design (with two comparison groups) explained in the preceding discussion was structured to test the following hypothesis:

- There are two major or important factors influencing the outcome of a trial, being treatment applied and gender differences.

- The residual ε of the model is independent and normally distributed with the mean 0 and variance σ. That is $\varepsilon = N(0,\sigma)$.

On the basis of the above assumptions and in consideration of the effects of the factors mentioned above, let Y be the performance of the *i*th gender after the *n*th training scheme. Thus the initial statistical model can be described in the following equation:

$$Y = M_{(n)} + G_{(i)} + \varepsilon \tag{6.5}$$

Where

- Y = The time of completing task/the number of errors/the number of trials of the *i*th gender by *n*th training scheme (n=1, 2D drawing; n=2, AR).

- M = the direct fixed effect for *n*th training scheme in the *i*th gender.

- G = the gender (i=1, male; i=2, female).

- $\varepsilon = N(0,\sigma)$, random fluctuations which are independent and normally distributed with the mean 0 and variance σ.

The tool used to analyse the data was SAS.

6.4.1. Results and Discussion

The raw experimental data was collected and then processed for further statistical analysis and interpretation. The results and discussion are presented as follows:

- Effect of Training Schemes on Number of Trials, Time and Error

In Table 21, the variations in the average amount of errors during each trial are presented. For the first trial, an average of 6.07 errors was made by the manual training group compared to 3.67 in the AR training group. For the second trial, an average of 3.13 errors made by the 14 trainees using the manual was significantly higher than those made by the AR trainees. As this post-training performance level relied on the memorising that was required in training phase. This indicator could reflect a certain level of difference in the WM effect.

Table 21. Training Schemes, Number of Trials and Mean Number of Errors in Formal Assembly for Experiment II

	AR TRAINING			**MANUAL TRAINING**		
Trial	**No. of people**	**Mean No. of error**	**No. of Person without error**	**No. of people**	**Mean No. of error**	**No. of Person without error**
1st	*14*	*3.67*	*0*	*14*	*6.07*	*0*
2nd	*14*	*1.10*	*9*	*14*	*3.13*	*1*
3rd	*6*	*0.00*	*6*	*14*	*0.86*	*7*
4th	--	--	--	*7*	*0.00*	*7*

Trainees with AR training could remember or recollect more assembly clues which had been memorised in the former training task than those trained with the manual prints. The elapsed mean time within each trial between two lots of training is depicted in Figure 39.

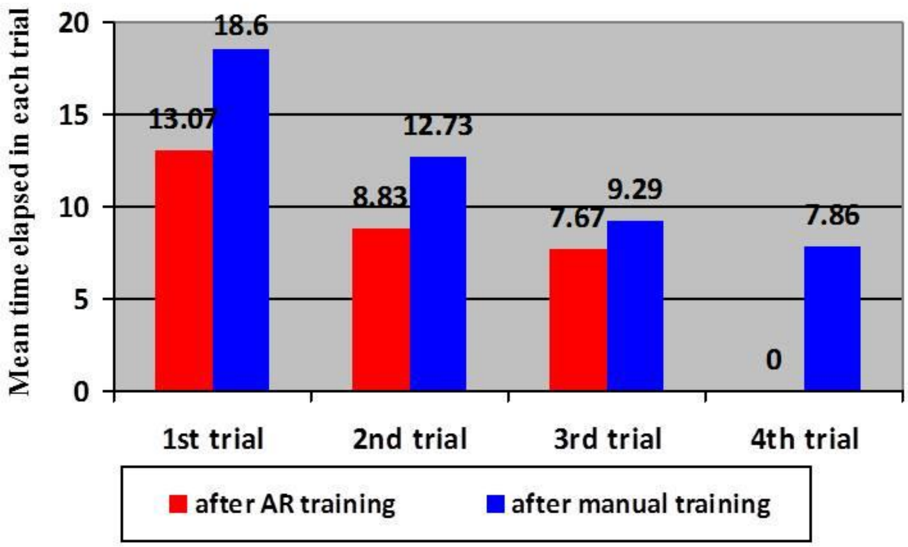


Figure 39. Average Time Elapsed Within Trial in Formal Assembly for Experiment II

A mean time of 13.07 minutes was needed for the trainees after AR training to complete the first trial, comparing with a mean time of 18.60 minutes for the trainees after manual training. With second and third trials, the time were 8.83 minutes (AR) vs. 12.73 minutes (manual) and 7.67 minutes (AR) vs. 9.29 minutes (manual), respectively. An ANOVA was conducted on the different effects of training on the time consumption of each trial. It is statistically significant that the mean time in the first trial (SD^{AR}=3.71, SD^{Manual}=2.72) is dependent on the individual training scheme (p value=0.00). Likewise, it is statistically significant for the second and third trial as well (for the second trial: p value=0.00, SD^{AR}=2.39, SD^{Manual}=3.15; for the third trial: p value=0.05, SD^{AR}=1.63, SD^{Manual}=1.59), as depicted in Table 22.

Table 22. Statistical Results for Time Eclipsing of Each Formal Trial for Experiment II

Trial	F value	P value	Significance
1st	*21.68*	*0.00*	*Significant*
2nd	*14.36*	*0.00*	*Significant*
3rd	*4.29*	*0.05*	*Significant*

More trials were obvious needed for the manual-based trainees complete the final trial without error. Eight testers in the AR training group were able to successfully complete the formal assembly after only two trials whereas no manual-based trainees were able to do so. By comparison, half of the trainees without AR conducted the third trial while the other half conducted the fourth. The performance curve for conducting formal assembly is given in Figure 40.

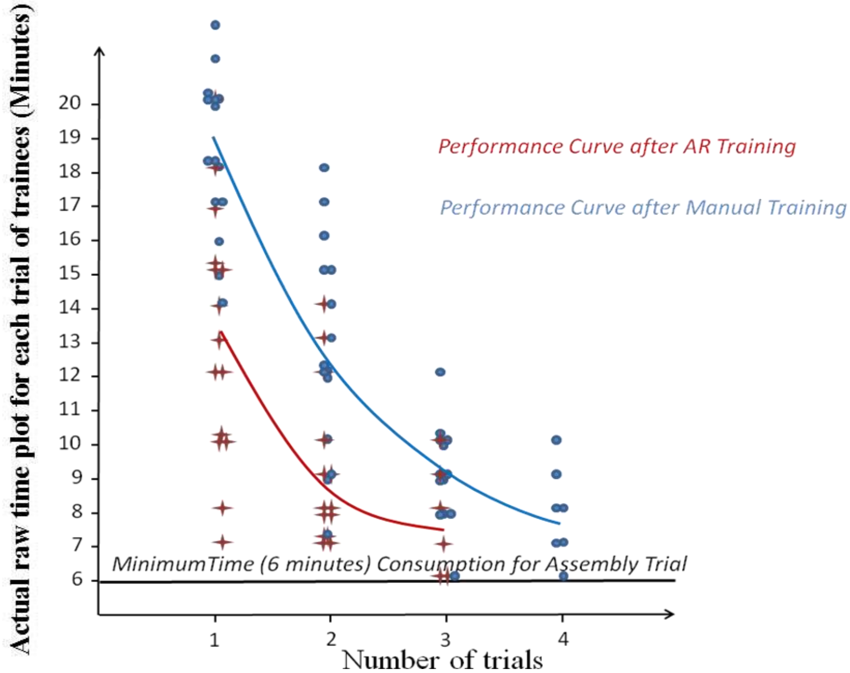


Figure 40. The Performance Curve for Conducting Formal Assembly between Training Schemes for Experiment II

The data illustrates that trainees under the AR training spent less time completing each formal assembly trial. To satisfactorily complete the assembly process within the specified time period (i.e. 6 mins) and without error or without acquiring additional information, trainees using AR required fewer trials (2.52) than those using manual training (3.5). Thus, to achieve a satisfactory training effect in terms of three measures, i.e., the number of assembly trials, time consumed to complete a trial, and number of errors, the AR trainees needed an average of 2.52 trial times ($\bar{t}$) and 24.83 minutes in total, while the manual-based trainees averaged 3.5 trial times ($\bar{t}$) and nearly 42.42 minutes in total. The total time is calculated in Equation 6.6:

$$Total = \bar{t} \times \overline{T}_{(t)} \tag{6.6}$$

Where

- *Total* = the total time of achieving a satisfactory training effect
- $\bar{t}$ = the mean number of trials
- $\overline{T}_{(t)}$ = the mean time consumption within each trial (t=1, 2, 3, 4)

The use of the animated AR system as a training tool shortens the learning curve of trainees in cognition-demanding assembly, and training in AR facilitates longer WM capacity compared with assembly manual-based training.

- The Analysis of Gender and Performance

Table 23 and 24 present the results of the different genders, quantitative data and statistical results for the post-training performance of the first trial. In the first trial with AR, the time consumed in real assembly tasks did not reflect the later evidence difference across genders, the results being: males: 13.14 minutes; females: 13.03 minutes). The p value of 1.00 also confirms the insignificance of this difference. It is however worthy to note this difference between manual trainees, as an average number of 17.14 minutes was spent by the male assemblers whilst 20.10 minutes were spent by the female assemblers, which is statistically supported by the p value of 0.03, as depicted in Table 23. The number of errors, as another indicator of the effects of gender difference, shows that both genders of AR trainees committed the same number of errors (3.60 errors) during the first assembly trial, and no difference was manifested (p value=0.81). Although female assemblers committed an average of 6.70 errors after manual training, an average of 1.1 errors more than male assemblers, the difference between genders was not significantly shown by the p value of 0.09, as depicted in Table 23. However, it is concluded that comparing with manual training, male and female trainees after AR training are able to achieve better performances in time and error in the first-to-start post-training task (males: 13.14 vs. 17.14 minutes, 3.70 vs. 5.60 errors; female: 13.03 vs. 20.10 minutes, 3.60 vs. 6.70 errors), which is statistically supported by the p values of 0.04 for males and 0.00 for females (time), and 0.04 for males and 0.00 for females (error), as depicted in Table 24.

Table 23. Statistical Results of Cross Gender in the First Trial in Experiment II (Within Training Scheme)

AR TRAINING						
Gender	**No. of people**	**Mean time**	**SS/df**	**F value**	**P value**	**Significance**
Male	*7*	*13.14*	*0.07/1*	*0.07*	*1.00*	*Insignificant*
Female	*7*	*13.03*				
		Mean error				
		3.70	*0.07/1*	*0.02*	*0.81*	*Insignificant*
		3.60				
MANUAL TRAINING						
Gender	**No. of people**	**Mean time**	**SS/df**	**F value**	**P value**	**Significance**
Male	*7*	*17.14*	*31.54/1*	*6.33*	*0.03*	*Significant*
Female	*7*	*20.10*				
		Mean error				
		5.60	*4.62/1*	*3.21*	*0.09*	*Insignificant*
		6.70				

Table 24. Statistical Results of Cross Training Schemes in the First Trial for Experiment II (Within Gender)

TIME						
	Male			**Female**		
	F value	**P value**	**Significance**	**F value**	**P value**	**Significance**
AR / **Manual**	*5.03*	*0.04*	*Significant*	*20.83*	*0.00*	*Significant*
ERROR						
	Male			**Female**		
	F value	**P value**	**Significance**	**F value**	**P value**	**Significance**
AR / **Manual**	*5.34*	*0.04*	*Significant*	*16.53*	*0.00*	*Significant*

The parallel findings were manifested in the second trial, as depicted in Table 24 and 25. The performance of both male and female trainees after AR training did not significantly vary in terms of time and error (8.57 vs. 9.10 minutes; 1.00 vs. 1.10 errors), whereas this varied significantly for those who used manual prints (11.14 vs. 14.32 minutes; 2.40 vs. 4.00 errors). After the manual training, the average time consumed for the female assemblers was 3 minutes more than for the male assemblers, while the number of errors was 1.6. The p values of 0.77 and 0.87 for time and error do not present the significant correlation of performance disparity in the AR group, whereas the p values of 0.04 and 0.05 support the significant disparity for the time and error between two genders of manual-based trainees, as depicted in Table 25. To complete the second trial, the manual-based trainees spent11.14 and 14.32 minutes, and committed 2.40 and 4.00 errors, an improvement on the first trial but still not as positive a score as the AR trainees in the same trial. This is statistically supported by the p values of 0.05 for males and 0.07 for females (time), and 0.03 for males and 0.00 for females (error), as depicted in Table 26.

Table 25. Statistical Results of Cross Gender in the Second Trial in Experiment II (Within Training Scheme)

AR TRAINING						
Gender	**No. of people**	**Mean time**	**SS/df**	**F value**	**P value**	**Significance**
Male	*7*	*8.57*	*0.64/1*	*0.09*	*0.77*	*Insignificant*
Female	*7*	*9.10*				
		Mean errors				
		1.00	*0.07/1*	*0.03*	*0.87*	*Insignificant*
		1.10				
MANUAL TRAINING						
Gender	**No. of people**	**Mean time**	**SS/df**	**F value**	**P value**	**Significance**
Male	*7*	*11.14*	*34.60/1*	*5.04*	*0.04*	*Significant*
Female	*7*	*14.32*				
		Mean errors				
		2.40	*5.79/1*	*4.50*	*0.05*	*Significant*

	4.00				

Table 26. Statistical Results of Cross Training Scheme in the Second Trial for Experiment II (Within Gender)

TIME						
	Male			**Female**		
	F value	**P value**	**Significance**	**F value**	**P value**	**Significance**
AR / **Manual**	*4.79*	*0.05*	*Significant*	*10.45*	*0.01*	*Significant*
ERROR						
	Male			**Female**		
	F value	**P value**	**Significance**	**F value**	**P value**	**Significance**
AR / **Manual**	*6.35*	*0.03*	*Significant*	*13.79*	*0.00*	*Significant*

Table 27 and 28 show the same measurements of the third and fourth trial respectively. For the AR group, only 3 male trainees and 3 female trainees needed to undertake the third trial, with an average of 7.67 minutes and no error was made. Since all the manual trainees had erred in the second trial, they were required to enter the third trial. The mean time of 8.57 and 10.10 minutes was spent and the mean number of 0.60 and 1.10 errors were made by two genders of manual trainees respectively. Differences are however proved to be insignificant by the p values of 0.09 (time) and 0.32 (error), as depicted in Table 27. Since only 6 trainees (3 male trainees and 3 female trainees) in the AR group had entered the third trial, the significance of performance difference for males and females between the AR and manual group is not valid (Table 28). It is thus concluded from the trend observed in the four trials, that as more trials are repeated, both training groups were able to improve their task performances. However, the AR group was able to achieve the required performance level with less number of trials than the manual group for both genders.

Table 27. Statistical Results of Cross Gender in the Third Trial for Experiment II (Within Training Scheme)

AR TRAINING						
Gender	**No. of people**	**Mean time**	**SS/df**	**F value**	**P value**	**Significance**
Male	*3*	*7.67*	--	--	--	--
Female	*3*	*7.67*				
		Mean errors				
		0.00	--	--	--	--
		0.00				
MANUAL TRAINING						
Gender	**No. of people**	**Mean time**	**SS/df**	**F value**	**P value**	**Significance**
Male	*7*	*8.57*	*7.14/1*	*3.33*	*0.09*	*Insignificant*
Female	*7*	*10.10*				
		Mean error				
		0.60	*1.14/1*	*1.09*	*0.32*	*Insignificant*
		1.10				

Table 28. Statistical Results of Cross Gender in the Fourth Trial for Experiment II (Within Training Scheme)

MANUAL TRAINING						
Gender	**No. of people**	**Mean time**	**SS/df**	**F value**	**P value**	**Significance**
Male	*3*	*7.00*	--	--	--	--
Female	*4*	*8.50*				
		Mean errors				
		0.00	--	--	--	--
		0.00				

Table 29 reports the statistical results for the correlation of task performance across each trial, which demonstrates that the time consumption and number of errors between the first and second trial significantly differ for both genders and training schemes (p values for AR: 0.03, 0.01, 0.04 and 0.05; for manual: 0.01, 0.01, 0.02 and 0.01). With the p values of 0.02, 0.00, 0.07 and 0.01 between trial two and three, the significance of performance difference for both genders in the manual group was statistically proven. Although the significance of task performance between trial two and trial three is not supported among AR trainees because of the limited number of participants in trial three, it was proven that AR training is more effective in shortening the learning curve for both male and female assemblers, and the carryover effect acquired from AR training is more durable.

Table 29. Statistical Results of Cross Trial for Experiment II (Within Gender)

MALE					**FEMALE**			
AR								
Time			**Error**		**Time**		**Error**	
P value					**P value**			
1^{st}–2^{nd}	*.03*	*Significant*	*.01*	*Significant*	*.04*	*Significant*	*.05*	*Significant*
2^{nd}–3^{rd}	--	--	--	--	--	--	--	--
MANUAL								
Time			**Error**		**Time**		**Error**	
P value					**P value**			
1^{st}-2^{nd}	*.01*	*Significant*	*.01*	*Significant*	*.02*	*Significant*	*.01*	*Significant*
2^{nd}-3^{rd}	*.02*	*Significant*	*.00*	*Significant*	*.07*	*Significant*	*.01*	*Significant*
3^{rd}-4^{th}	--	--	--	--	--	--	--	--

- Model Analysis

A two-way ANOVA test was implemented into the statistical model with the data from the experiments and the results from the SAS system illustrated in Table 30. Firstly, there is the main effect of the training scheme, where a significant difference in post-training performance can be found between the AR training and the manual training groups, as indicated by p values of 0.01 and 0.01. Although the factor of gender does not show a significant effect on post-training performance from an overall observation (p values of 0.11 and 0.08), it does show a significant effect on the manual training group, as supported by p values of 0.03 and 0.09 in Table 22 and 0.04 and 0.05 in Table 24. This indicates that AR is equally effective in improving task performances for both genders, whereas manual-based training is more effective for male assemblers only. The training schemes applied and gender differences can be represented by factor M*G. The p values of 0.01 and 0.02 show that the interaction was significantly presented in the first two trials when manual training was applied. Therefore, there is significance in the training scheme with regard to gender interaction in the manual-based training group, and both interact in their effects on post-training performance. Therefore, the statistical model becomes:

For AR training:

$$Y = M_{(n)} + \varepsilon \tag{6.7}$$

For manual training:

$$Y = M_{(n)} + G_{(i)} + \varepsilon \tag{6.8}$$

Table 30. Statistical Results of Two-way ANOVA Test for Experiment II

FIRST TRIAL					
Source	**DF**	**Mean square**	**F value**	**P value**	**Significance**
Gender (G)	*1*	*10.32*	*1.88*	*0.11*	*Insignificant*
Method (M)	*1*	*231.14*	*14.86*	*0.01*	*Significant*
Gender*Method (G*M)	*1*	*4.66*	*8.82*	*0.01*	*Significant*
SECOND TRIAL					
Source	**DF**	**Mean square**	**F value**	**P value**	**Significance**
Gender (G)	*1*	*12.56*	*3.64*	*0.08*	*Insignificant*
Method (M)	*1*	*187.39*	*12.88*	*0.01*	*Significant*
Gender*Method (G*M)	*1*	*7.49*	*9.31*	*0.02*	*Significant*

Based on the collected statistical data, the performance curve for both males and females conducting real assembly is given in Figure 41. The AR training is able to generate parallel learning curves across male and female assemblers. In other words, AR training is equally effective for both males and females. Assemblers after AR training are able to achieve better performance compared with those who do not use AR. However, training with the assembly manual is more effective for male assemblers, as female assemblers typically spend more time completing each formal assembly trial and they committed more errors within each trial. It is also concluded that regardless of gender, AR can provide more effective training outcomes for assembly novices than the 3D manuals. The reason for the positive training results is due to the better effect of information recall. The hypothesis that ‘AR training facilitates the WM for longer and shortens the learning curve of trainees (learn faster)’ (*H3*) is validated.

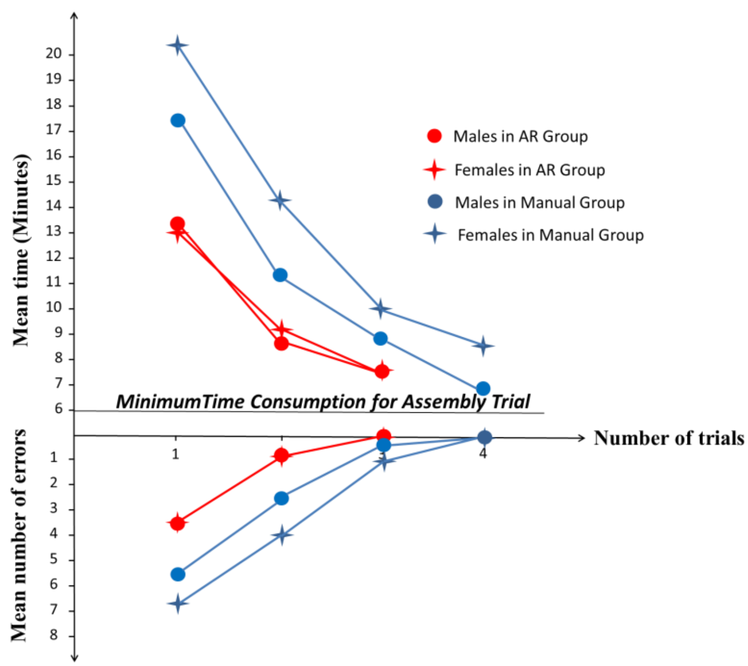


Figure 41. The Performance Curve of Conducting Formal Assembly between Training Schemes and Genders for Experiment II

Given that the methodology of addressing the theoretical issues is based on task performance research, Figure 42 further investigates the number of trainees who erred in the 9th step. The 9th step was the one regarded as the most 'prone-to-error' throughout the entire assembly, as there was more than one way of connecting components, yet the correct one was unique. It was observed that most of the trainees committed errors in this step. In the first trial, 9 AR trainees, out of 14 had erred in conducting the correct installation whereas 7 of them no longer erred in following trial. By comparison, 13 and 8 manual trainees (respectively) erred in the 9th step in both trials respectively, indicating that most manual trainees had forgotten how to install that particular component even though they had done so twice. This performance difference between the two training schemes was in fact reflected as efficiency in memorising. AR visualisation is more apt to help with memorising. and the maintenance and recovery period afterwards. It could be suggested that the better memorising effect derives from effective training which emphasises the relevant memory cue (cultivates memory association), decreases mental effort (lowers burden of mental searching) and forms memory associations (inhibits rehearsal competition). The cognitive support of animated AR visualisation is in line with the formation of the information processing model, which emphasises the impact of visualisation on sparing mental resources and inhibiting rehearsal competition. Information flow for particular assembly tasks generated in AR can be effective in assisting in identifying the mental operations that take place in the processing of various types of information from input to output. The cognitive load in cognition-demanding task begins involving deeper mental process of estimating the first trial position and comparing the results with the target position, i.e., making adjustments. The amount of mental resources that could be set aside and the extent of the rehearsal competition that can be inhibited usually depends on the workload of conducting cognitive activities. This emphasis supports the conclusion that sparing or conserving the mental resources of trainees can be achieved by an enhanced work-piece scene and strengthened memorising effect, and the disparity of post-training performance is determined by memory searching, association and rehearsal competition. Therefore, *H3* is validated.

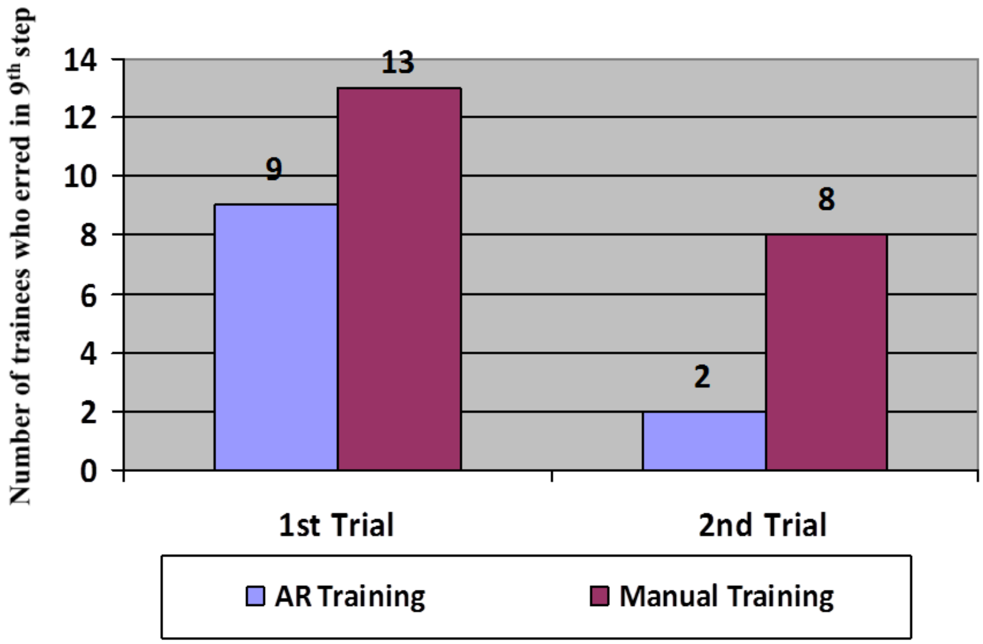


Figure 42. The Statistics of Trainees that Erred in the 9th Step of Formal Assembly for Experiment II

CHAPTER 7. USEABILITY EVALUATION

7.1. Methodology

User-centred evaluation includes a set of methods where an evaluator inspects and develops complex user interfaces (UIs), and can generally be used in the early stages of system development by evaluating prototypes or specifications for the system to be tested by users (Hartso et al. 2001). The formative assessment and summary assessment are two common methods for user-centred evaluation (Wang, Xiangyu 2006, 131). The formative assessment typically involves qualitative feedback, and is a range of formal and informal assessment procedures employed by observers during the learning process in order to modify UI to improve learning activities. Summary assessment seeks to monitor educational outcomes, and is often used for purposes of external accountability (Shepard 2005). As a quick, cheap and easy method for finding and assessing useability problems in a UI design as part of an iterative design process, an heuristic evaluation is also conducted in this research. As pluralistic inspection and activity analysis requires more people to inspect the scenario for problems and they are more focused on the actual work of the human in the field rather than the UI design, they are not going to be used in this research. To sum up, the formative assessment and the heuristic evaluation are used as the methodology presented herein. Although the concept of combining formative user assessment and heuristic evaluation is not necessarily new, applying these methods to AR UI is novel.

7.2. Formative Assessment

The participants conducting AR treatment in two experiments were involved in the formative assessment to collect system useability data through the post-session questionnaire. Sample results of questions and useability suggestions are illustrated in Table 31. The first column lists the useability issues considered; the second gives the mean rating value for each useability issue from the opinions of users; the third explains which interface component or interaction techniques involve the useability issue and the reasons for this. The results are presented as follows.

Table 31. Results and Interpretation of Useability Analysis for the Animated AR System

Scale: 1 2 3 4 5 6 7

(Very little) (Very much)

Issues	Mean	Summarised Results
Navigation		
Did you often feel disoriented?	*2.6*	*A little disoriented* *Users felt a little disoriented with nothing in the augmented scene for the navigational cues or landmarks.*
Did the surrounding real background help your spatial comprehension?	*5.3*	*Slightly apparent* *This is one of the advantages of AR over manual prints.*
Input Mechanism		
Did you feel annoyed or inconvenienced when operating keyboards or markers to view different angles of virtual images?	*2.3*	*Very positive* *Although there are still some system drawbacks, the user still expressed a positive attitude towards the system controls.*
Visual Output		
Did visual output have adequate stability of the images as you moved with no perceivable distortions in visual images?	*4.8*	*Neutral* *It seems that the system lag is tolerable and does not affect the perception of the visual images of users and therefore does not affect their performance.*
Was the FOV (field of view) appropriate for supporting this activity?	*5.7*	*Very appropriate* *The broader the projection, the better sense the user has of the environment and of their communication with the AR system.*

Did the monitor-based visual display create difficulties for observation?	*2.4*	*Very easy* *Users felt the large projection or TV monitor was easy to watch while performing the LEGO assembly task. This was unlike the HMD, which tended to result in cumbersome and uncomfortable feelings; the monitor is robust enough to support assembly.*
Did you believe the virtual images could be spatially matched with the physical counterparts?	*5.3*	*Slightly positive* *The user felt that the virtual augmented components of LEGO could be spatially matched with the physical components. Therefore, this characteristic facilitates the comparison and selection of assembly components.*
Was the AR display effective in conveying convincing scenes of models appearing as if in the real world?	*4.4*	*Neutral* *The virtual model appears to be floating into the air of the real environment. A neutral rating implies that the combination of virtual model and real world approaches seamlessness to some extent.*
Immersion		
With the AR system, were you isolated from and not distracted by outside activities?	*4.3*	*Neutral* *It seems that the users did not feel greatly distracted by outside activities by being isolated, which implies that the AR system might be useful in focusing users' minds on the task.*
Comfort		
Was the AR system comfortable for long-term use?	*5.8*	*Very comfortable* *A very high score demonstrates the acceptability of the animated AR system. It is not bulky, does not trigger user fatigue, or limit user mobility.*
Did you experience excessive eye fatigue?	*2.0*	*Very little* *Usually, subjects only watched the monitor for about 20 minutes for the training process. If the user has to watch it for longer time, eye fatigue might appear.*

Did you experience high levels of general discomfort during interaction with AR system?	*2.1*	*Little* *As for the above item. This section refers to any general discomfort (visual, audio, mobility) for the whole system.*
After-effect		
Did you experience any of the following after exposure to the AR system: "blurred vision", "dizziness"; "nausea"; "difficulty focusing" or "loss of vertical orientation"?	*No*	*All participants specified "NO"* *During the experiment, the subjects interacted with the system for only 20 minutes for the training process. After this, they used the system for observing some specific guiding steps. Using the system for longer may have caused nausea.*
Would you embrace the opportunity to use the AR system again in the future?	*Yes: 72.5%*	*Most participants embraced the idea of using the AR system for guiding assembly tasks in the future.*

7.3. Heuristic Evaluation

Heuristic evaluation was conducted for improving the UI of the animated AR system. Since the design of AR UI is still in its nascent stages, a standard set of useability guidelines does not exist. Molich and Nielsen (1990) developed a set of heuristics that are probably the most used in the field of interface design. After evaluating several sets of heuristics, Nielsen (1994) later came up with a better set, including visibility of system status, match between system and the real world, user control and freedom, and error prevention. Hvannberg, Law and Lárusdóttir (2007) refined a research agenda for comparing and contrasting evaluation methods, and presented a framework to evaluate the effectiveness of different types of support for structured useability problems. These useability guidelines provide a reasonable starting point for useability evaluation of the animated AR system. Table 32 is the heuristic evaluation, where the design guidelines, the useability problems and the recommendation are listed. The possible results from heuristic evaluation can subsequently be used to remedy obvious and critical useability problems along with aiding the design of the above formative evaluation.

Table 32. Results of Heuristic Evaluation for the animated AR System

Framework "Useability Guideline	**Potential Useability Problem**	**Recommendation**
AR-based social environments (e.g., games), allow users to create, present, and customise private and group-wide information.	*Subjective annotation functionality is not enabled in the current system.*	*Efficient annotation techniques and associated protocol should be developed. An effective way is to assign an annotator or coordinator that is capable of observing the whole collaborative process via monitor or projector. His/her annotation can be presented to collaborators after the session.*
When assessing appropriate tracking technology relative to user tasks, one should consider working volume, desired range of motion, accuracy and precision required, and likelihood of tracker occlusion.	*The current tracking technology is vision-based marker tracking that has the disadvantages of limited working volume, short range of motion, and tracking occlusion. The current tracking system does not support long ranges, which cannot support mobile users.*	*Identify more sophisticated and appropriate tracking systems such as LED high-ball systems that are optical tracking system developed by UNC.*

CHAPTER 8. SUMMARIES AND CONCLUSIONS

8.1. Summaries and Conclusions

This dissertation started with scoping a structured methodology for applying an AR-based approach to the tasks of assembly. The aim of the research was to assess the effectiveness of AR-based animation in facilitating effective and efficient assembly performance, and effective training of people involved in the assembly tasks which are made up of many different parts and elements. Based on the formulated methodology, a prototype system called the animated AR system was successfully developed. The evaluation of three assembly scenarios was implemented with regard to both benefits validation and useability evaluation. Two experiments devised to assess the discrepancies between the traditional guidance and AR were undertaken. Results from the experiments indicate a positive effect on cognitive facilitations when using the animated AR system in assembly tasks. When trainees relied upon their memory and the manual to complete an assembly, they were prone to making errors. When AR was used, the learning curve of trainees was markedly shortened.

Specifically, the quantitative findings based on the experiments point to the facts that: compared with the 3D manual, AR reduces the time taken to successfully complete an assembly by 38 percent and reduces the number of errors by 62 percent. AR also helps both male and female trainees learn the assembly routine faster (less trials and time within each trial were needed, see Figure 39 and Figure 40); compared with the 2D isometric drawings. AR reduces 50 percent of the total time (55% original time and 46% rework time were saved), 50 percent of error and saves on payments to assemblers (original time and rework time were reduced). AR also saves 2/3 cost of correcting erroneous assembly for both 3D manual prints and 2D isometric drawings. AR significantly lowers the cognitive workload. Other findings include that AR training is more effective for both male and female assemblers than the 3D manual, whereas training with the 3D manual is more effective for male assemblers than female assemblers.

The six contributions of this paper to the area of research are listed as follows:

- Developing the theoretical framework, which summarises the existing mechanisms concerning the visuo-spatial information processing and the WM processing in the context of spatial cognition theory, active vision theory and the WM theory. The framework also raised the to-be-validated aspects of the above theories when transferring from the psychological arena to practical instances. The hypotheses tested in the two experiments were derived from the above theoretical framework.

- Devising three particular assembly scenarios that are normally guided by traditional visualisations (3D manual prints/2D isometric drawings) and that can be tested with two experiments.

- Prototyping the animated AR system in aiding small-scale and real-scale assembly.

- Quantitatively and qualitatively verifying that animated AR visualisation can be used as an effective alternative to traditional visualisations. Such effectiveness is also applied to the theoretical mechanisms of visuo-spatial information processing and WM processing. The theoretical assumptions are validated: AR animation can enhance the work-piece scene, set aside more mental resources and inhibit rehearsal competition. In line with psychological theories, these findings could further uphold the theories from a practical perspective.

- Implementing heuristic and formative useability evaluations for the animated AR system. Improving suggestions for enhancing future use in real projects.

This research provides an empirical impetus for similar improvements in the use AR technology for guiding workers in the field of construction assembly. In particular, it is suggested from the results that AR could be used in guiding novices to carry out assembly tasks where training time is limited and errors are either dangerous or costly.

These findings can be generalised in a wide range of assembly practices. For example, mechanics in mechanical engineering shares the same mechanism of assembly with assemblers in construction area. Thus, it is regarded that such novel assembly guidance can be also widely applied in mechanical assembly trial. Besides, these findings may directly recognise the mechanisms concerning visuo-spatial information processing and WM processing that are reflected in physical task performance, which in turn helps explore the to-be-validated aspects of spatial cognition theory, active vision theory and the WM theory when transferring from the psychological arena to practical instances.

8.2. Recommendations for Future Work

Future work will hopefully lead to the implementation of the AR system into real construction projects. The real improvements in performance and productivity with AR can be then measured and quantified with site assembly activities in a real project context. The transfer of the animated AR system from laboratory-based applications to real construction applications has higher potential for system flexibility and tracking, e.g. to enable assembly in a limited way in construction sites. Using portable AR devices such as wireless HMD or cameras will enable more stable tracking (images won't be lost when occluding the path between tracking targets and camera). Where the tracking targets (markers) are not able to be pasted, markerless tracking techniques such as tracking using the salient geometric features of real spatial objects might be adopted. Since tracking is one of the most essential elements in determining whether the AR system is effective or not in real projects, future work should focus on the integration of the current tracking technologies and develop more robust tracking methods.

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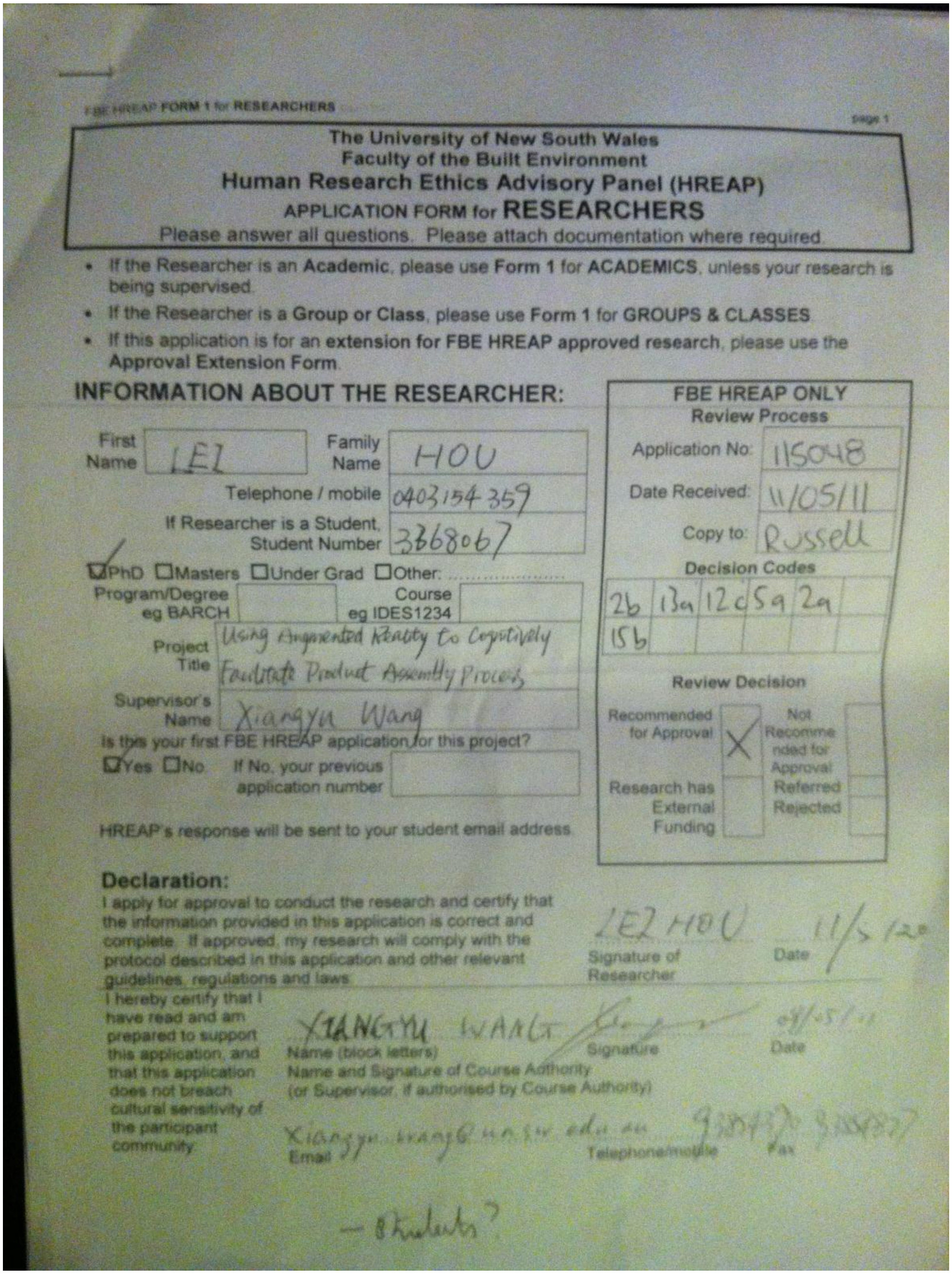
APPENDICES

Appendix A: Form 1: Human Research Ethics Advisory Panel (HREAP) Application Form for Researchers



FBE HREAP FORM 1 for RESEARCHERS

page 1

The University of New South Wales
Faculty of the Built Environment
Human Research Ethics Advisory Panel (HREAP)
APPLICATION FORM for RESEARCHERS

Please answer all questions. Please attach documentation where required.

- If the Researcher is an **Academic**, please use **Form 1** for **ACADEMICS**, unless your research is being supervised.
- If the Researcher is a **Group or Class**, please use **Form 1** for **GROUPS & CLASSES**
- If this application is for an **extension for FBE HREAP approved research**, please use the **Approval Extension Form**.

INFORMATION ABOUT THE RESEARCHER:

First Name	LEI
Family Name	HOU
Telephone / mobile	0403154359
If Researcher is a Student, Student Number	3368067

☑PhD ☐Masters ☐Under Grad ☐Other: ....

Program/Degree eg BARCH	
Course eg IDES1234	
Project Title	Using Augmented Reality to Cognitively Facilitate Product Assembly Process
Supervisor's Name	Xiangyu Wang

Is this your first FBE HREAP application for this project?

☑Yes ☐No If No, your previous application number

HREAP's response will be sent to your student email address.

FBE HREAP ONLY

Review Process

Application No:	115048
Date Received:	11/05/11
Copy to:	Russell

Decision Codes

2b	13a	12c	5a	2a	
15b					

Review Decision

Recommended for Approval	X	Not Recommended for Approval	
Research has External Funding		Referred	
		Rejected	

Declaration:

I apply for approval to conduct the research and certify that the information provided in this application is correct and complete. If approved, my research will comply with the protocol described in this application and other relevant guidelines, regulations and laws.

LEI HOU — Signature of Researcher — Date 11/5/2011

I hereby certify that I have read and am prepared to support this application, and that this application does not breach cultural sensitivity of the participant community.

XIANGYU WANG — Name (block letters) — Signature — Date 09/05/11

Name and Signature of Course Authority (or Supervisor, if authorised by Course Authority)

Xiangyu.wang@unsw.edu.au — Email — Telephone/mobile 93854370 — Fax 93854827

— Students?

INFORMATION ABOUT THE RESEARCH:

Please answer EVERY question below by ticking the YES box if it applies to your research or the NO box if it doesn't apply.

If you tick the YES boxes, additional documents are required to accompany this application. The required additional documents are indicated by ■

Additional documents required

Question		FORM 2 PARTICIPANTS	FORM 3 PROJECT INFORMATION STATEMENT	FORM 4 PROJECT CONSENT FORM	FORM 5 PRIVACY & CONFIDENTIALITY	FORM 6 LETTER OF SUPPORT	RISK MANAGEMENT FIELDWORK APPLICATION REQUIRED
1. Will you be selecting or approaching people to take part in your project?	☑ YES ☐ NO						
2. Will you be requiring people to answer a questionnaire? (A questionnaire is a list of standard questions voluntarily answered by participants who are not identifiable.)	☑ YES ☐ NO						
3. Will you be interviewing people or requiring people to participate in a focus group? (An interview involves interaction between the researcher and the participant. Participants may be identifiable.)	☐ YES ☑ NO						
4. Will you be making recordings of people (photographic, audio or video)? (Do not tick the YES box if your research involves recording members of the public engaged in lawful pursuits in public places.)	☑ YES ☐ NO						
5. Is there a possibility of people being inappropriately identified, or confidential data being divulged during or after your research?	☐ YES ☑ NO						
6. Will your research require you to deceive or mislead any person?	☐ YES ☑ NO						
7. Will you be using records or database information from sources other than the public record?	☐ YES ☑ NO						
8. Are there organisations other than UNSW involved in your research (eg shop owner, government department, contractor, business, another university)?	☐ YES ☑ NO						
9. Is your research being partly or completely funded by an agency, business, or other party outside the UNSW?	☐ YES ☑ NO						
10. Do you have any conflict of interest (including financial gain) in regard to this project?	☐ YES ☑ NO						
11. Is there real potential for physical, psychological, social, cultural or financial harm to occur during your research or as a result of your research?	☐ YES ☑ NO						

FBE HREAP **FORM 1** for **RESEARCHERS** page 3

CHECKLIST:

Please tick to indicate that you have attached the following documents in support of your application.

Compulsory:

- ☑ **FORM 1 for RESEARCHERS** (this form)
- ☑ Please provide a **DESCRIPTION OF THE PROJECT** (about 300 words) on a separate sheet that indicates your:
  - a. Aims
  - b. Hypothesis / research questions
  - c. Methodology
  - d. Project timing / schedule

  This explains the project to FBE HREAP.

Additional Documents to accompany your application:

If you answered YES to any of the questions on the previous page, some or all of the following forms must accompany this application:

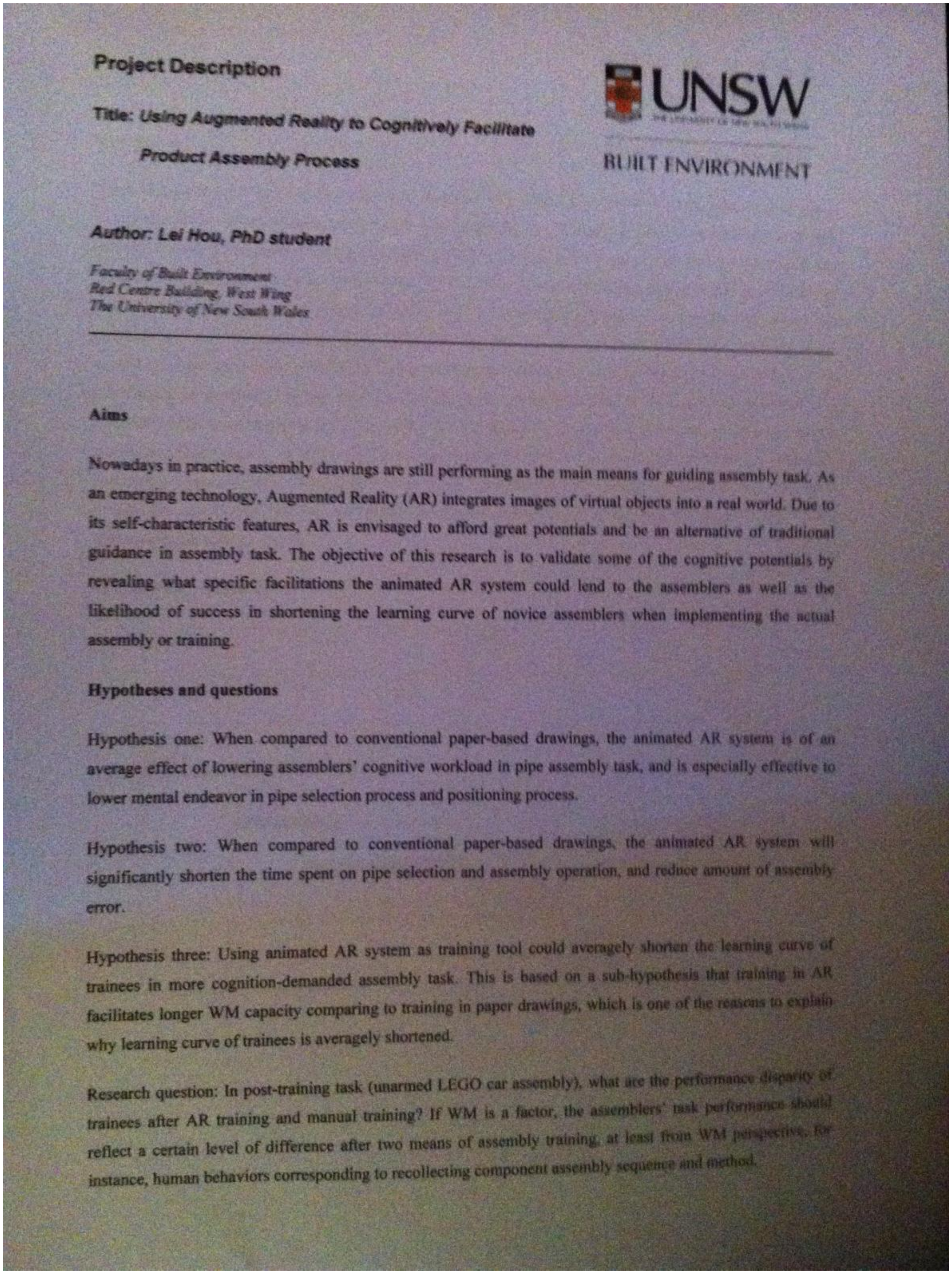
- ☑ **FORM 2 – PARTICIPANTS**
  Print the form and answer every question.
- ☑ **FORM 3 – PROJECT INFORMATION STATEMENT**
  Edit the standard template on line by following the directions in italics. *Then print and sign the edited form.*
- ☑ **FORM 4 – CONSENT FORM**
  Edit the standard template on line by adding the title of *the project and the name of the* Researcher. Then print the edited form. Do not ask the *participants to sign the form until after* your application has been approved.
- ☑ **FORM 5 – PRIVACY & CONFIDENTIALITY**
  Print the form and answer every question.
- ☐ **FORM 6 – LETTER OF SUPPORT**
  Letters of Support are not required for FBE HREAP to recommend approval, but must be obtained as part of your research arrangements and a copy sent to FBE HREAP to complete your file. Include in your application a list of the organisations that will be asked to provide a Letter of Support.
- ☑ Copy of your proposed **QUESTIONNAIRE**, which must show affiliation with UNSW.
- ☐ List of the proposed **INTERVIEW or FOCUS GROUP QUESTIONS**.

Additional Documents to prepare but are not part of your application:

- ☐ If **FIELDWORK** approval is required, refer to:
  http://www.fbe.unsw.edu.au/FBEguide/fbeOHS/downloads/fieldworkapplication.rtf

PLEASE SUBMIT THE ORIGINAL AND THREE COPIES OF ALL DOCUMENTS.

Appendix B: Description of the Project on a Separate Sheet



Project Description

Title: ***Using Augmented Reality to Cognitively Facilitate Product Assembly Process***

UNSW
BUILT ENVIRONMENT

Author: Lei Hou, PhD student

Faculty of Built Environment
Red Centre Building, West Wing
The University of New South Wales

Aims

Nowadays in practice, assembly drawings are still performing as the main means for guiding assembly task. As an emerging technology, Augmented Reality (AR) integrates images of virtual objects into a real world. Due to its self-characteristic features, AR is envisaged to afford great potentials and be an alternative of traditional guidance in assembly task. The objective of this research is to validate some of the cognitive potentials by revealing what specific facilitations the animated AR system could lend to the assemblers as well as the likelihood of success in shortening the learning curve of novice assemblers when implementing the actual assembly or training.

Hypotheses and questions

Hypothesis one: When compared to conventional paper-based drawings, the animated AR system is of an average effect of lowering assemblers' cognitive workload in pipe assembly task, and is especially effective to lower mental endeavor in pipe selection process and positioning process.

Hypothesis two: When compared to conventional paper-based drawings, the animated AR system will significantly shorten the time spent on pipe selection and assembly operation, and reduce amount of assembly error.

Hypothesis three: Using animated AR system as training tool could averagely shorten the learning curve of trainees in more cognition-demanded assembly task. This is based on a sub-hypothesis that training in AR facilitates longer WM capacity comparing to training in paper drawings, which is one of the reasons to explain why learning curve of trainees is averagely shortened.

Research question: In post-training task (unarmed LEGO car assembly), what are the performance disparity of trainees after AR training and manual training? If WM is a factor, the assemblers' task performance should reflect a certain level of difference after two means of assembly training, at least from WM perspective, for instance, human behaviors corresponding to recollecting component assembly sequence and method.

UNSW

BUILT ENVIRONMENT

Methodology

There are two one quiz and two experiments to be conducted. Before the experiment, participants will be tested in a quiz called 'mental rotation task', which is to guarantee all participants have the approximate cognitive capacity (variable elimination strategy). At the same time, the animated AR system will be prototyped and experimental platform will be set up based on two assembly tasks (down-scaled pipe assembly and LEGO car assembly) that are chosen on purpose. Then it follows the implementation of experimentation, where the performances will be measured by subjective metric—the NASA Task Load Index (Hart, 2006), questionnaires, as well as objective metrics—task performance observation and time recording. Students will be invited as the participants of experiment to perform the assembly tasks under experimental setup, and the guidance of a sampling procedure that previously constituted will be prepared for the students to understand the experimental procedure. Furthermore, an associated usability questionnaire will be developed in order to assess the participatory process and certain features of AR space. Last but not least, statistical model will be developed to arrange the experimental sessions and collect data. Statistical analysis tool (SAS) will be used to test inter-factor correlations for reliable results.

Project Time / Schedule

First year		Second year		Third year		Fourth year	
1st	2nd	1st	2nd	1st	2nd	1st	2nd
Literature review							
	Writing proposal						
		Prototyping					
				Human ethics & Pilot study			
					Experimentation & Analysis		
					Thesis writing & submission		

Appendix C: Form 2: Participants

P FORM 2 – PARTICIPANTS page 1

TICIPANTS

se answer each of the following questions and provide details as required. If there is not enough ce provided on this form, please attach the information on a separate sheet.

Will you be selecting or approaching people to take part in your project?

☑ YES

- Please explain the procedure you intend to use to attract, approach or select the participants, and the process for evaluation of their suitability.

I am going to invite students (participants) accordi email. Using email list of different faculties, i am able notify some students. I will let them know the aim, proce and time consumption of experiments and they can reply me if agree to atten

- If you will be briefing the participants, please provide details about this.

In the email, i will explain the ~~expte~~ ~~experiment~~ experiments procedure briefly so that they could have a basic understandi about what they will do. When they are in my experimental s i will also let them read a detailed instruction about what they shou do exactly.

- If you will be advertising for participants, please attach your proposed advertisement, poster, letter or other advertising media.

☐ NO

- Please explain how you will be conducting your research without selecting or approaching people.

2. Will any of the participants be younger than 18 years of age?

☐ YES

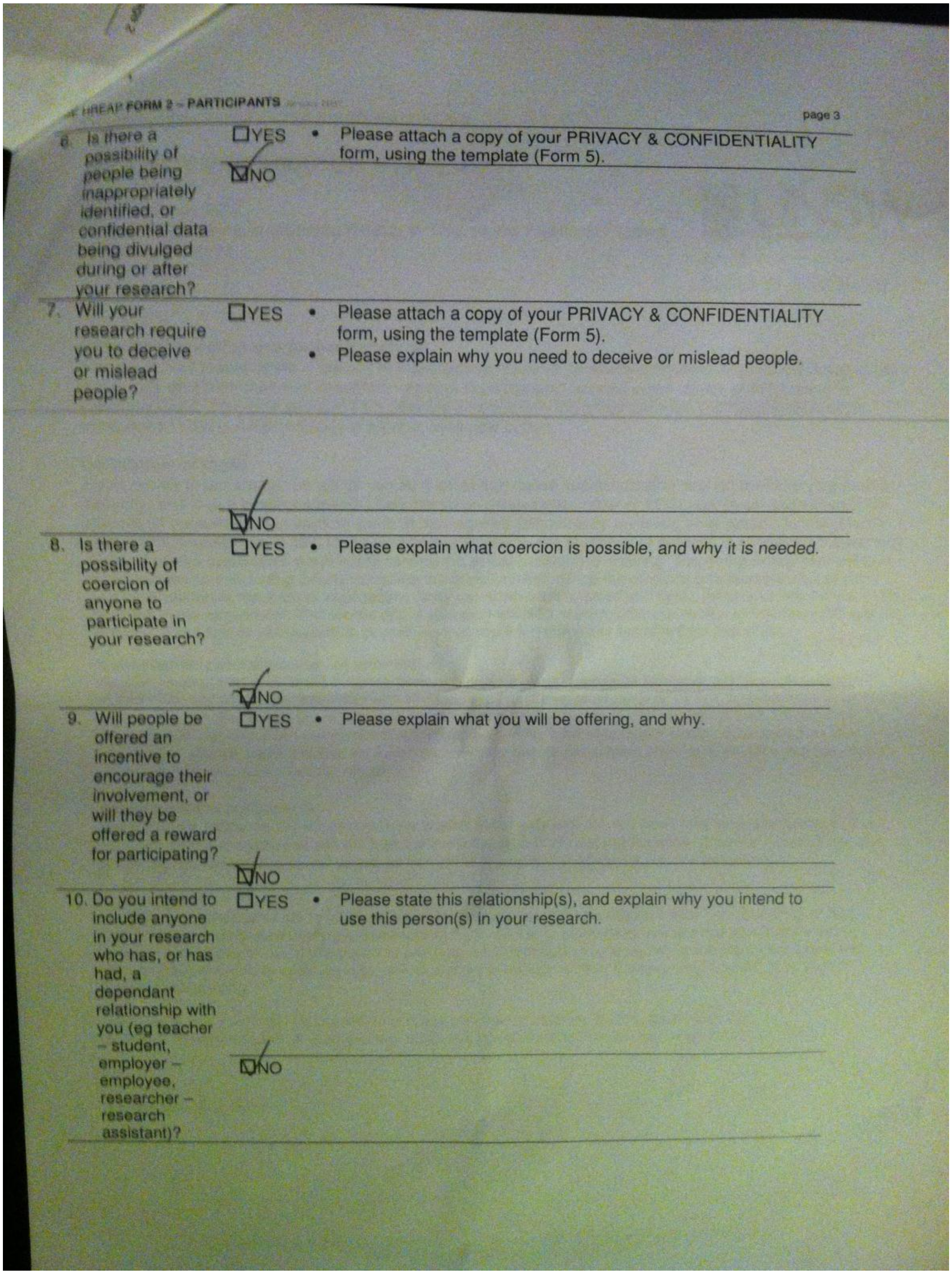
- Generally, the BE panel cannot approve research involving minors. Either apply directly to the UNSW HRE committee or attach documentation containing substantial evidence that your research will be conducted under the direct supervision of the minor's guardian, or that other appropriate protection of each minor will be guaranteed.

☑ NO

- Please explain how you will ensure that none of your participants are minors.

In the invitation email, i will highlight that ~~participan~~ if they're under 18, they are not qualified to be participants. When they come to my experimental setup, i will also double check their IDs to make sure they're older than 18 years of age

3. Will you be requiring people to answer a questionnaire? (A questionnaire is a list of standard questions voluntarily answered by participants who are not identifiable.)	☒YES	• The questionnaire is required to be on UNSW letterhead and include the name of the project and your name and university contact details. When the questionnaire is used, your PROJECT INFORMATION STATEMENT must accompany it. Please attach a copy of the questionnaire, in English, and your Project Information Statement. Use the Form 3 template for your Project Information Statement. • Please attach a copy of your PRIVACY & CONFIDENTIALITY form, using the Form 5 template.
	☐NO	
4. Will you be interviewing people or requiring people to participate in a focus group? (An interview involves interaction between the researcher and the participant. Participants may be identifiable.)	☐YES	• Each interviewee or member of a focus group must give their written consent in response to their receipt of your PROJECT INFORMATION STATEMENT. Please attach a copy of your Project Information Statement and your proposed PROJECT CONSENT FORM, using the templates (Forms 3 & 4) for these documents. • Please attach a copy of your PRIVACY & CONFIDENTIALITY form, using the template (Form 5). • Please list the questions and/or range of issues that you will cover with the interviewees or focus group members.
	☒NO	
5. Will you be making photographic, audio or video recordings of people? (Do not tick the YES box if your research involves recording members of the public engaged in lawful pursuits in public places.)	☒YES	• Please attach a copy of your PRIVACY & CONFIDENTIALITY form, using the template (Form 5). • Please explain why you need to make recordings as part of your research. I am going to record participants' ~~ontasl~~ ongoing task performance (assemble some models) from which i am able to caculate how many error assembly they will make and how long they will spend to complete assembly tasks. • Please explain how these recordings will be done, and by whom. Before experiments, i am going to borrow the recorder from IT service desk, During experiment, i will fix it on a bracket. When participants start to assemble models, i will start recording. To every participant, i am going to let he/she know they will be recorded before the experiments.
	☐NO	



HREAP FORM 2 – PARTICIPANTS

page 3

6. Is there a possibility of people being inappropriately identified, or confidential data being divulged during or after your research?	☐YES	• Please attach a copy of your PRIVACY & CONFIDENTIALITY form, using the template (Form 5).
	☑NO	
7. Will your research require you to deceive or mislead people?	☐YES	• Please attach a copy of your PRIVACY & CONFIDENTIALITY form, using the template (Form 5). • Please explain why you need to deceive or mislead people.
	☑NO	
8. Is there a possibility of coercion of anyone to participate in your research?	☐YES	• Please explain what coercion is possible, and why *it is needed.*
	☑NO	
9. Will people be offered an incentive to encourage their involvement, or will they be offered a reward for participating?	☐YES	• Please explain what you will be offering, and why.
	☑NO	
10. Do you intend to include anyone in your research who has, or has had, a dependant relationship with you (eg teacher – student, employer – employee, researcher – research assistant)?	☐YES	• Please state this relationship(s), and explain why you intend to use this person(s) in your research.
	☑NO	

Appendix D: Form 3: A Sample of Project Information Statement

HREAP FORM 3 – PROJECT INFORMATION STATEMENT January 2007

page 1

PROJECT INFORMATION STATEMENT

Date: 12 May, 2011

Project Title: Using Augmented Reality to Cognitively Facilitate Product Assembly Process

UNSW THE UNIVERSITY OF NEW SOUTH WALES

BUILT ENVIRONMENT

Approval No.: 115048

Participant selection and purpose of study

You are invited to participate in a study of investigating cognitive facilitations of using Augmented Reality (AR) technology as an alternative of conventional paper drawings and learning curve issues of AR training in assembly tasks. You were selected as a possible participant in this study because you have seldom or no experience of trying AR technology in product assembly before.

Description of study

If you decide to participate, we will let you do a small quiz called 'mental rotation' first (to evaluate your spatial capacity) and then a product assembly task based on real-scaled pipe or LEGO car (main experiment). The purpose of experiment is to validate some of the cognitive potentials by revealing what specific facilitations the animated AR system could lend to the assemblers as well as the likelihood of success in shortening the learning curve of novice assemblers when implementing the actual assembly or training. The entire experiment will take about half an hour including time to complete the questionnaire. Since the products to assemble are not from real construction or mechanical applications (they are down-scaled, small and light), there is no risk for you to be involved in our experiment. The results of this research will lead to more effective design of animated AR system. But we cannot and do not guarantee or promise that you will receive any benefits from this study.

Confidentiality and disclosure of information

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission, or except as required by law. If you give us your permission, we plan to use the results/data to do the analysis in a thesis of PhD student of Built Environment. If possible, we plan to publish our research outcomes to journals, book chapters or conferences based on your permission. We will guarantee that we won't disclose your private information anywhere, anytime and the results will only be used in pure scientific research.

Recompense to participants

Since you are invited as the volunteers to participant in our experiments, we won't offer any remuneration. But we could offer you candies or soft drink as the rewards for your kindest participation. After the experiments, you will be always welcome to try our improved version of animated AR system if you are interested.

Your consent

Your decision whether or not to participate will not prejudice your future relations with The University of New South Wales or other participating organisations. If you decide to participate, you are free to withdraw your consent and to discontinue participation at any time without prejudice by completing the statement below and returning this entire form to Mr Lei Hou, a PhD student in Faculty of Built Environment, Level 6, Red Centre Building, West Wing.

If you have any questions, please feel free to ask Lei (Ext: 55259; email address: z3368067@unsw.edu.au). If you have any additional questions later, Lei will be happy to answer them.

Complaints may be directed to the Ethics Secretariat, The University of New South Wales, SYDNEY 2052 AUSTRALIA (Tel: 9385 4234, Fax: 9385 6648, Email: ethics.sec@unsw.edu.au)

Please sign your name: Jason

BE HREAP **FORM 3 – PROJECT INFORMATION STATEMENT** January 2007 page 2

REVOCATION OF CONSENT. Project Title: Using Augmented Reality to Cognitively Facilitate Product

(Please send this entire form to the above address.)

I hereby wish to withdraw my consent to participate in this research project. I understand that such withdrawal will not jeopardise my relationship with The University of New South Wales, other participating organisations or other professionals.

....	....	....
Signature	Please PRINT name	Date

Appendix E: Form 4: A Sample of Project Consent Form

PROJECT CONSENT FORM

UNSW
BUILT ENVIRONMENT

Project Title: Using Augmented Reality to Cognitively Facilitate Product Assembly Process

You are making a decision whether or not to participate in a research project.

This PROJECT CONSENT FORM enables you to indicate your preparedness to participate in the project. By signing this form, your signature indicates that you have decided to participate.

You will be given a PROJECT INFORMATION STATEMENT that explains the project in detail, and that statement includes a revocation clause for you to use if you decide to withdraw your consent at some later stage. The PROJECT INFORMATION STATEMENT is your record of participation in the project.

This PROJECT CONSENT FORM will be retained by the researcher as evidence of your agreement to participate in this project.

Please complete the information in this box.

Please indicate which of the following options you agree to by ticking one of the following options.

- [x] I consent to being quoted and identified
- [ ] I do not want to be quoted or identified but am prepared to participate anonymously

Jason
....
Signature of Research Participant

JASON
....
Please PRINT name

06/07/11
....
Date

Name of researcher: Lei Hou

Appendix F: Form 5: Privacy & Confidentiality

HREAP FORM 5 – PRIVACY & CONFIDENTIALITY

PRIVACY & CONFIDENTIALITY

Page 1

Please answer each of the following questions and provide details as required. If there is not enough space provided on this form, please attach the information on a separate sheet.

1. Will you be using records or database information from sources other than the public record?	☐YES ☑NO	• Please tick the appropriate box(es) below if you will be identifying, collecting, using, or disclosing health information of a personal nature about individuals without their consent, from any of these sources: ☐ Commonwealth departments or agencies ☐ State departments or agencies ☐ Other third parties such as non-government agencies. If you ticked any of these boxes, you will need to provide additional information. Please ask a HREAP member for details. • Written consent is required from the owner / manager for the use of data from sources other than the public record. Please attach a copy of your PROJECT CONSENT FORM, to be signed by the owner / manager, using the template (Form 4). • Please provide details about the proposed sources of this information and the type of information being sought.
2. Do you have any conflict of interest (including financial gain) in regard to this project?	☐YES ☑NO	• Please explain the conflict of interest and how you intend to manage it.
3. Do you intend to keep all your original data and records? (Examples of records are project consent forms, letters of support, questionnaires, recordings.)	☑YES ☐NO	• Destroying any of your original data or records inhibits the verification of your research, restricts the future publishing of your work, and limits your defences against litigation. • Please list the data or records you intend to destroy and explain why and how they will be destroyed.

BE HREAP **FORM 5 – PRIVACY & CONFIDENTIALITY**

page 2

4. Will your data and records be stored in a secure location for a minimum of 5 years after completion / publication and be accessible, if requested, by the Head of School?

☐YES • Please detail where your data and records are to be stored (type of storage and the physical address).

☑NO • Please explain what you intend to do with your data and records.

I will only use these data to do the experimental analysis and i will involve the results in my PHD thesis. After i submit my thesis, i am not going to use these data or disclose them.

5. Will you be making photographic, audio or video recordings of people?

☑YES
- You do not need to get prior consent to record members of the public engaged in lawful pursuits in public places.
- If you intend to record in a different situation, or if a person objects to you recording them, please explain how you will ensure that each person is made aware of the purpose of your recording and that their anonymity is protected.

I will let know them the aim of video recording, which is [illegible] get quantitative data from it, e.g. numbers for error assembly operations, component selection, time consumption etc. I will also show them Form 3 to convince them that no personal [illegible] will be [illegible]

- If you intend to ask for written consent from the person(s) being recorded, please attach a copy of your PROJECT CONSENT FORM, using the template (Form 4).

☐NO

6. Do you propose to de-brief participants in your research, or provide an opportunity for participants to review, vet, or edit your findings? (A de-brief is carried out after your research has been done.)

☑YES • Please explain how you intend to do this.

If possible, the thesis will be published in journals, book chapters or conferences. Every participant gets the chance to access the research findings. Also, before publication, every participant is welcome to review, vet or edit the findings.

☐NO • Please explain why you do not intend to do this.

Appendix G: Responses for FBE Ethics Advisory Panel

RESPONSES FOR FBE ETHICS ADVISORY PANEL

Applicant: Lei Hou

Student ID: 3368067

To FBE ethics advisory panel,

Thanks very much for the approval of my ethics application. The following is the feedback of your comments.

Comment 1: It is unclear who is being surveyed and how they will be selected or approached.

This research focuses on the cognitive issues that related to assembly tasks (pipe assembly and Lego model assembly). Specifically, the aim of this research is to validate some cognitive facilitations of using AR technology as an alternative of conventional assembly drawings and investigate the training effects or learning curve issues of AR training. This does not necessarily mean that only the real assemblers from industrial areas are the candidates for experimental participants. Instead, we prefer that the 'novice assemblers' are more suitable to be our experimental participants or testers. Therefore, we intended to make a wide selection of participants from students in our campus.

The experiments need about 70 participants from our university and they will be contacted or approached by email. Using different email lists from different faculties of UNSW, we are trying to get them contacted.

Comment 2: The information provided in your application about the timing of your research is either too vague or implies that the research may have already started.

This research was started two years ago in Sydney Uni, the university where I transferred from. Currently, it is the third year of my research in UNSW. Here I confirm that all research requiring ethics approval has not commenced.

As you require the details of the proposed timing of the research, here I am going to explain them.

Mar, 2009 to Feb, 2010—The first year of my PhD study. During this year, I finished literature review, research proposal writing, annual progress review and probation. (Sydney Uni)

Mar, 2010 to Feb, 2011—The second year of my PhD study. During this year, I finished AR system prototyping and experimental design and annual progress review. (Sydney Uni)

Mar, 2011 to May, 2011—In the first month after my transfer, I was preparing the ethics application. I submitted the application on 12 May and I have got the approval letter since 17 May, 2011. (UNSW)

Jun, 2011 to Sep 2011—I will be carrying out the research experiments. (UNSW)

Sep 2011—I will write my PhD thesis. (UNSW)

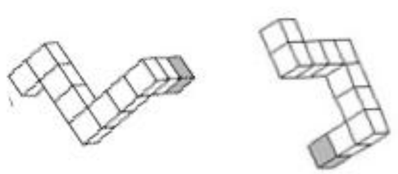
Comment 3: Please provide HREAP with further information about the how and where your data is going to be stored (ie, type of storage and precise storage address).

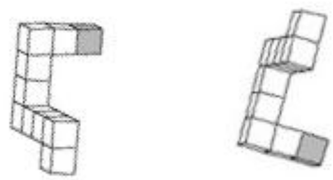
The experimental data contain questionnaires and videorecording (stored in U disk). They will be stored in my private cabinet in the lab in level 6 (EXT 55259) of Red Building, West Wing and I will be the only one who holds the keys for the cabinet until I graduate from UNSW.

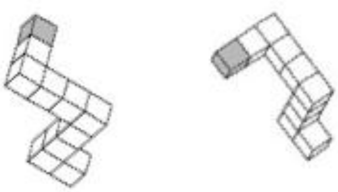
After that, I will store them in my own strong box in my house, and I will be the only one who knows the password to access.

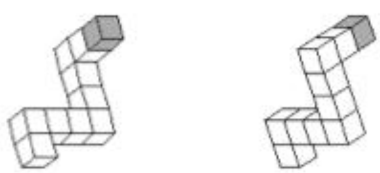
Appendix H: Mental Rotation Test Sheet

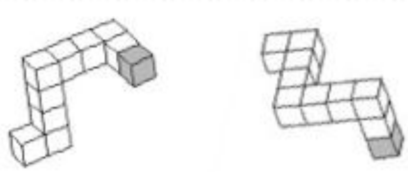
1. SAMF or NOT?

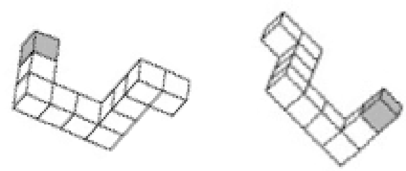


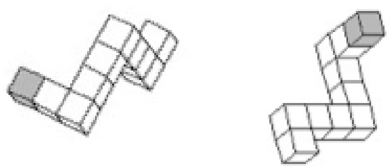




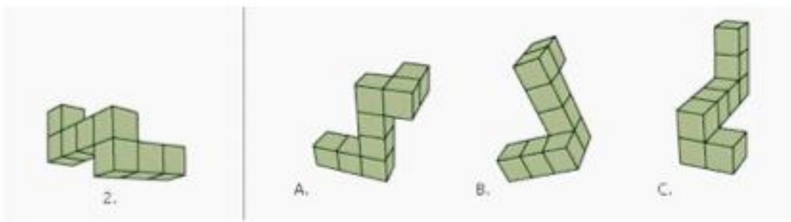


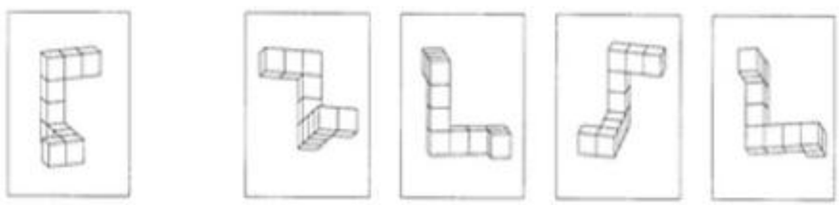


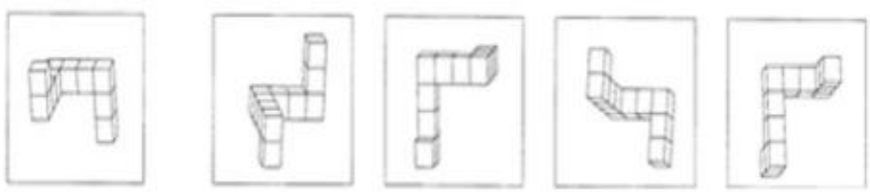


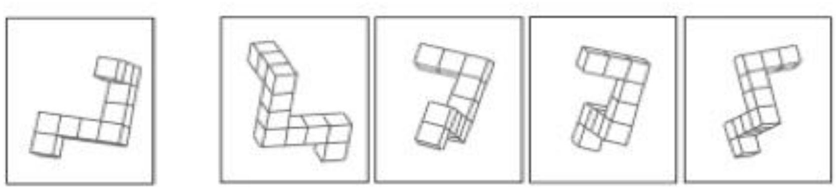


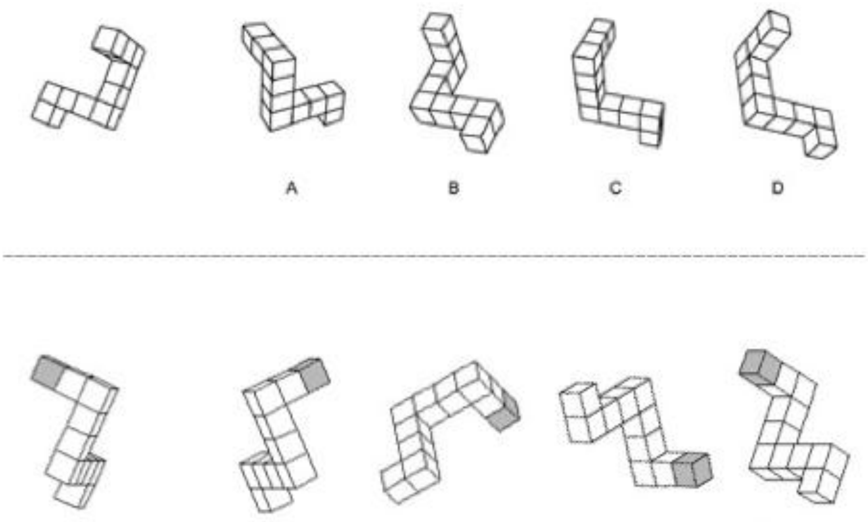
2. Which is the right version of 'LEFT' cube?



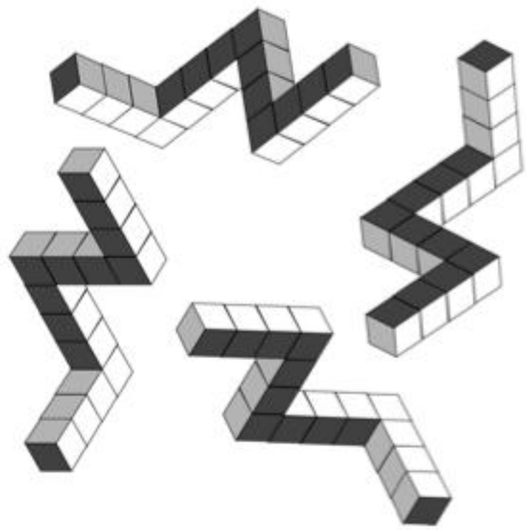


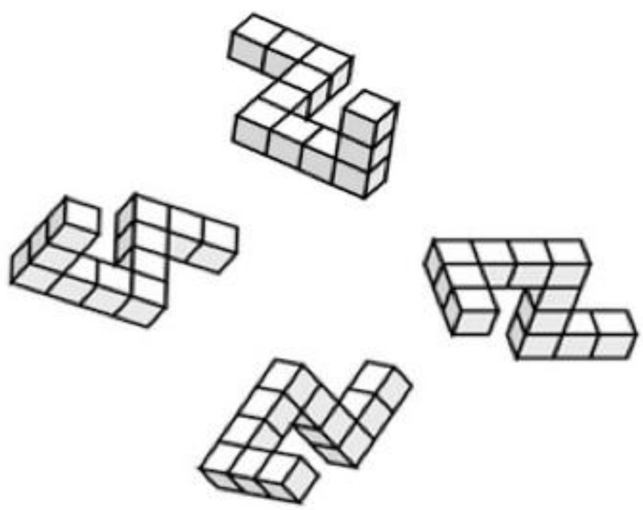





A
B
C
D

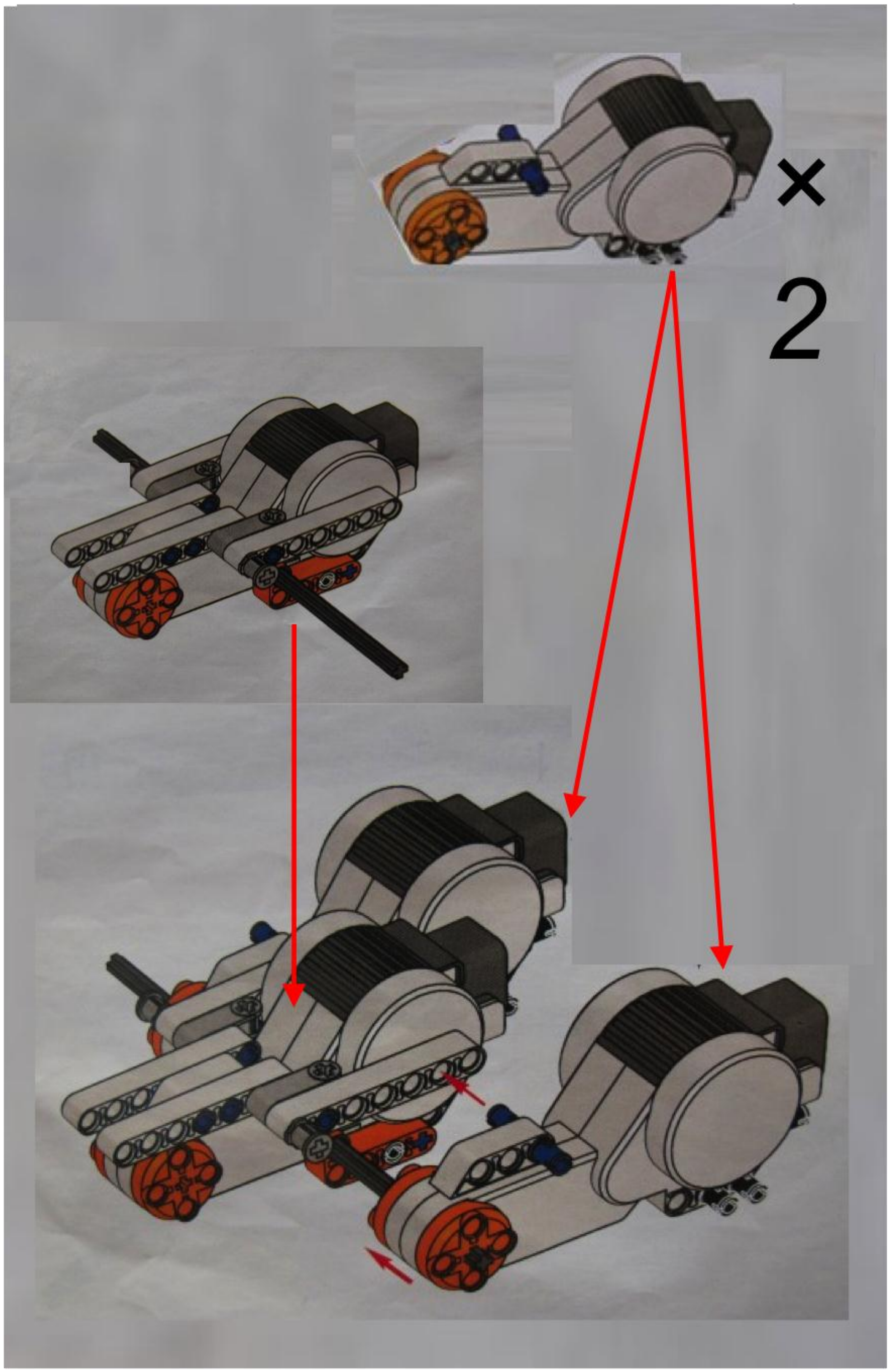
3. Which one is different from other three?





Appendix I: 3D Manual Prints for Assembling LEGO Model

1



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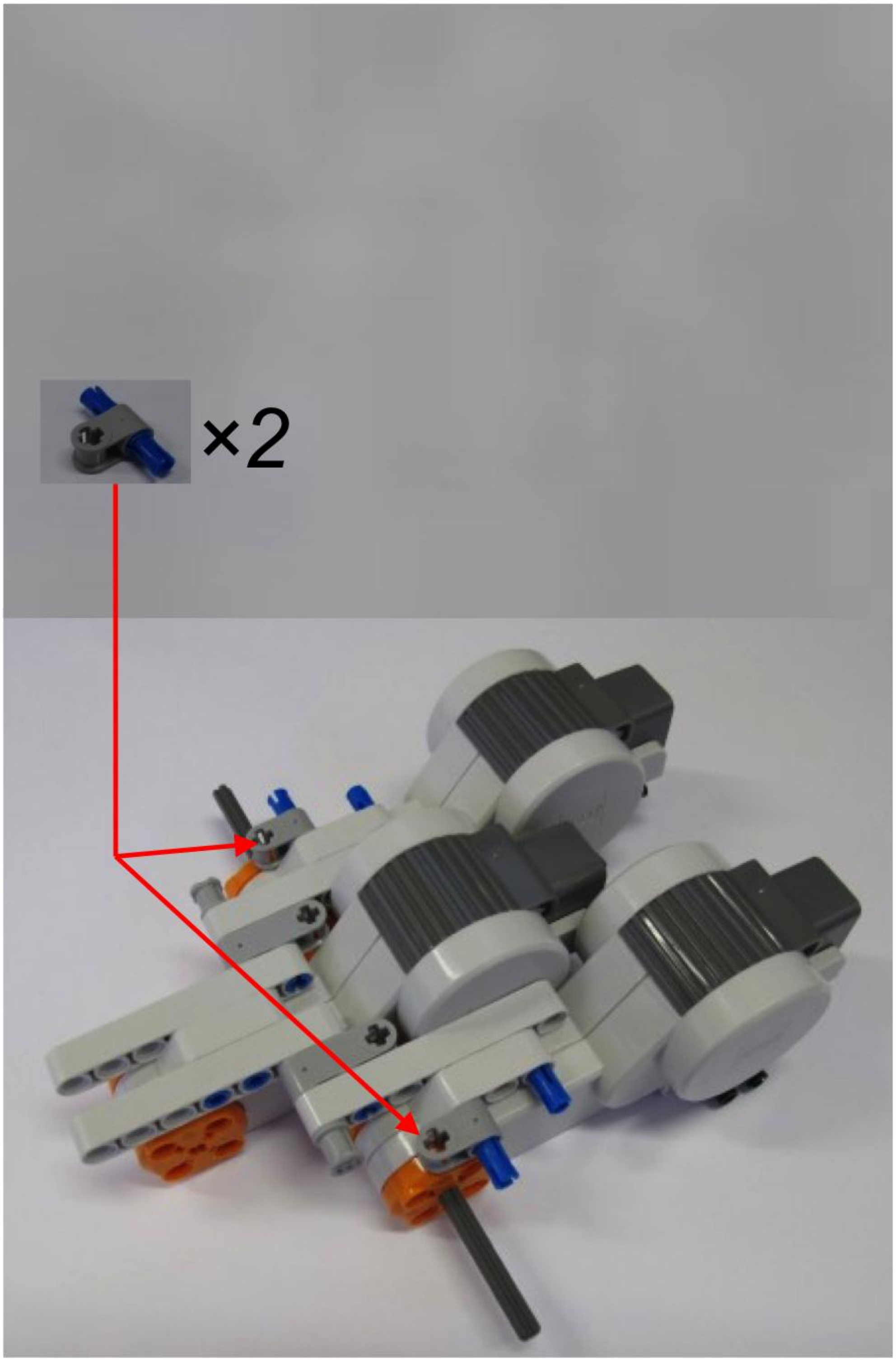

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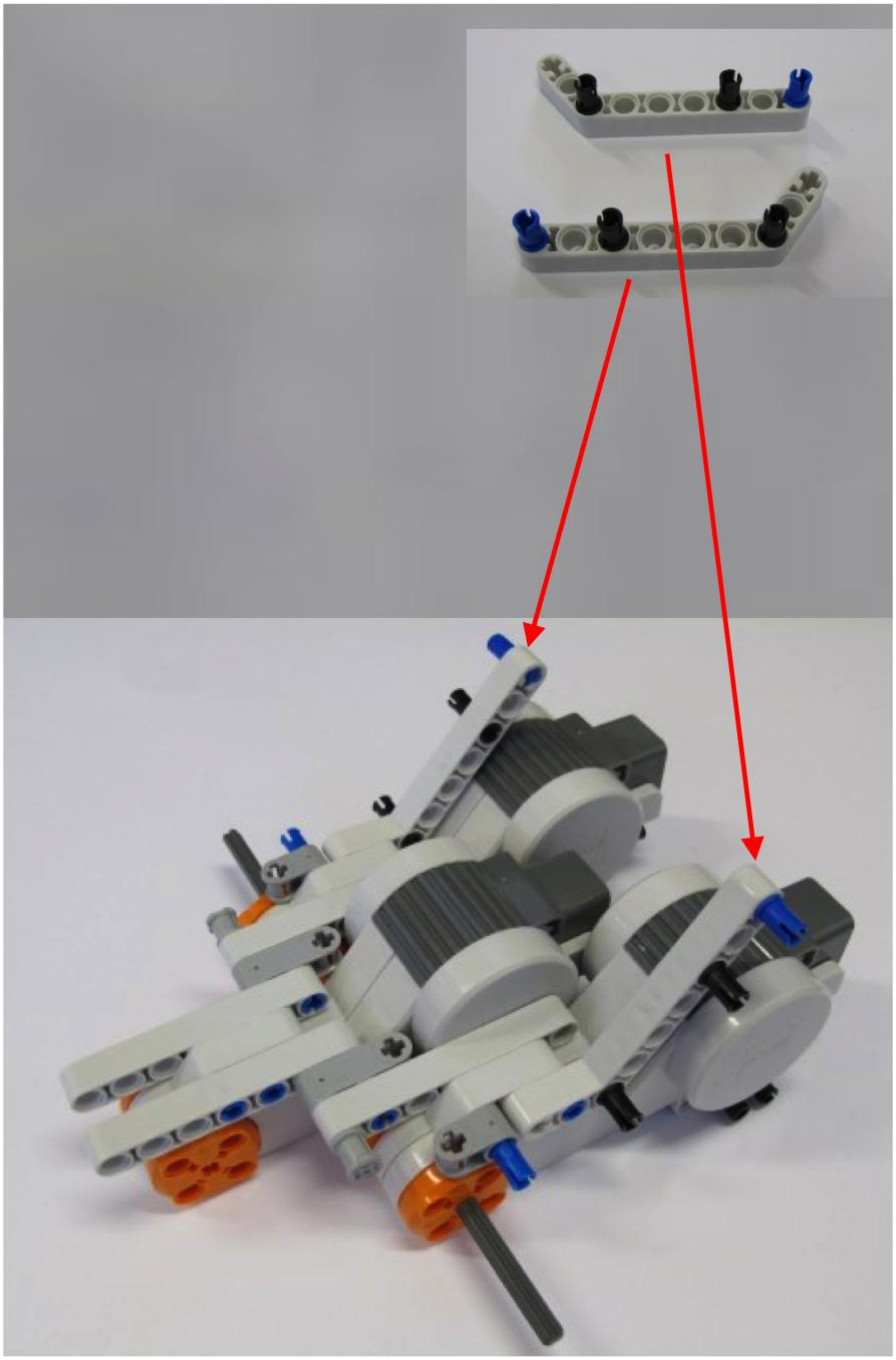

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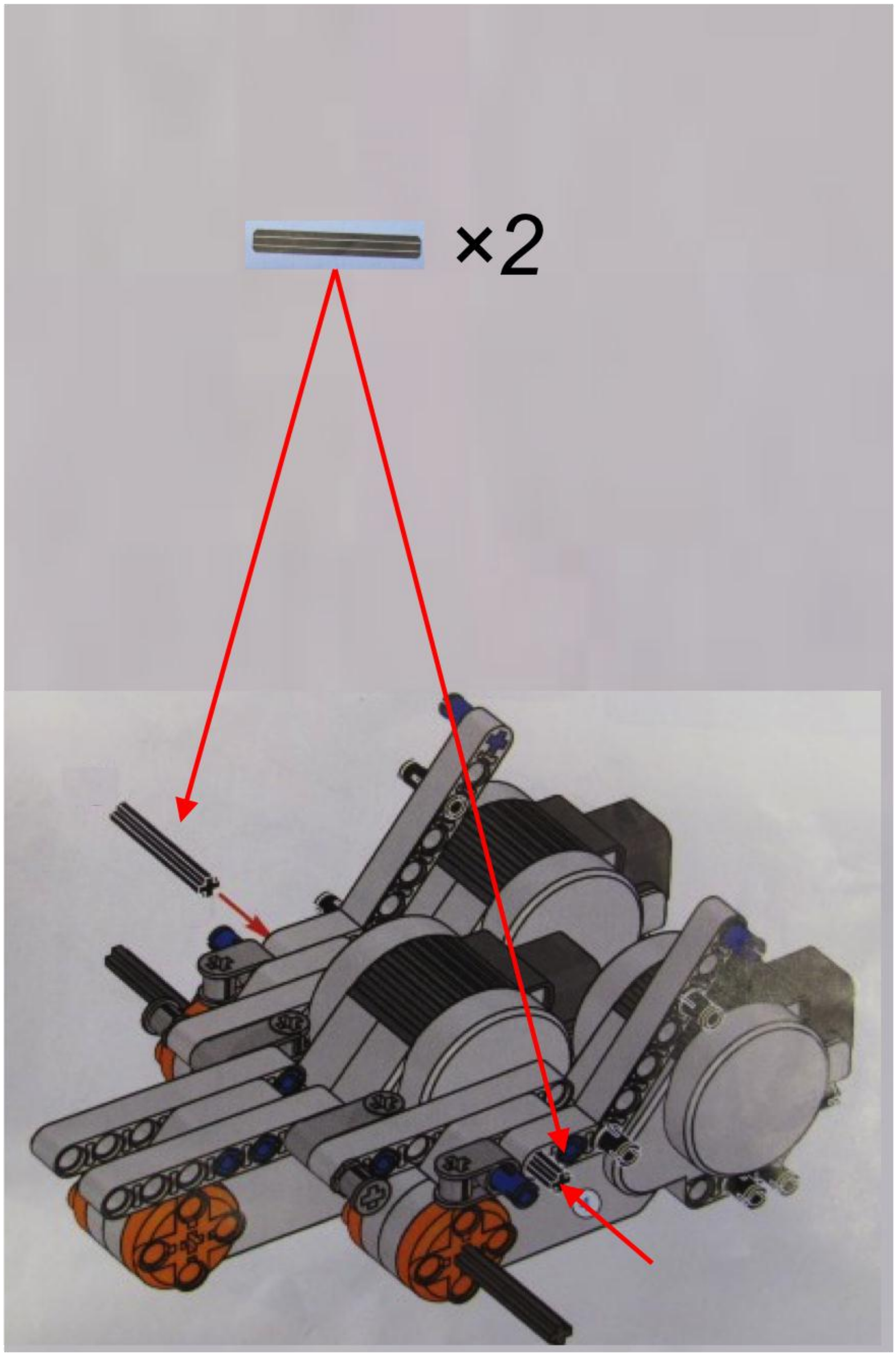

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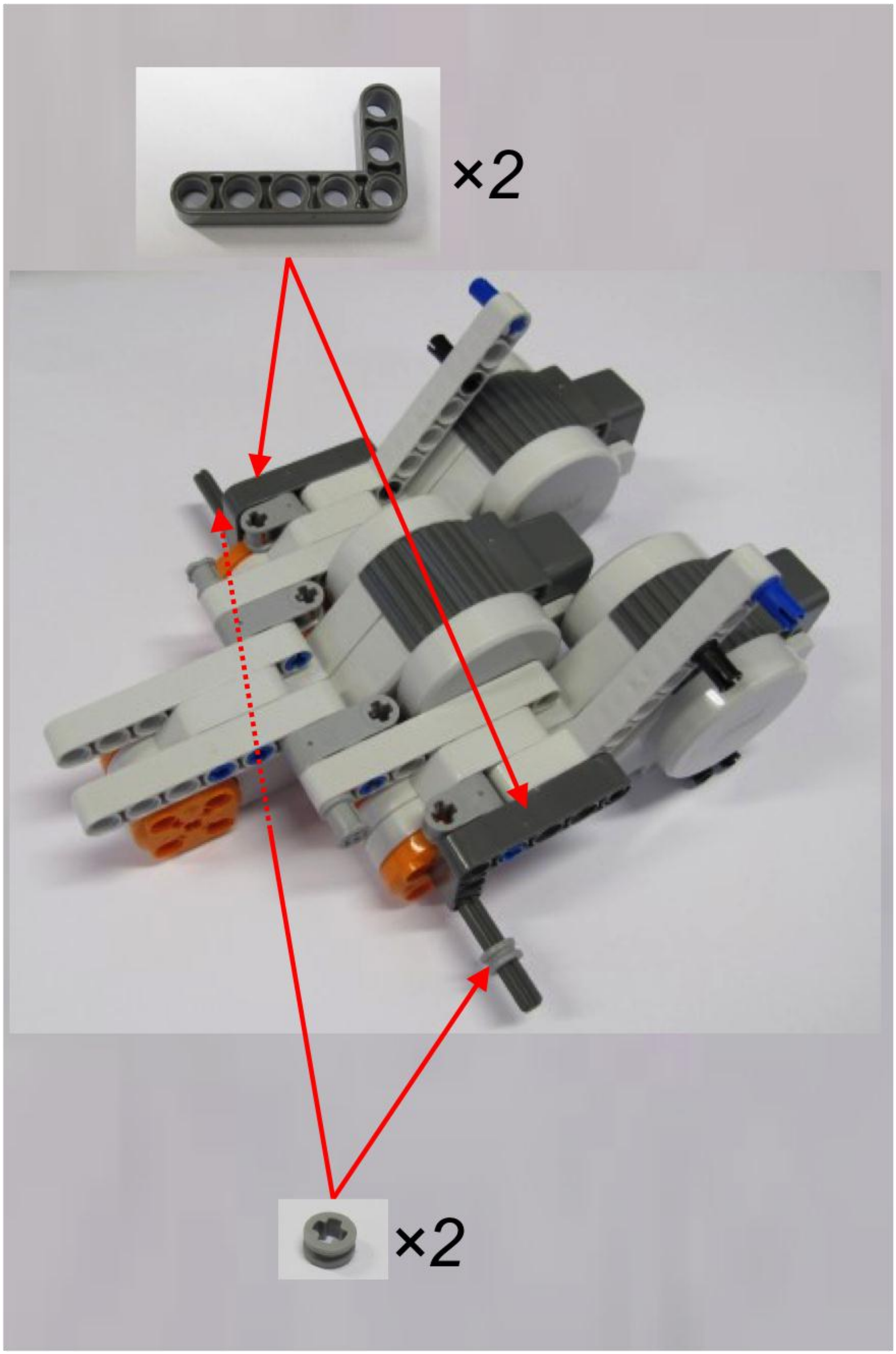

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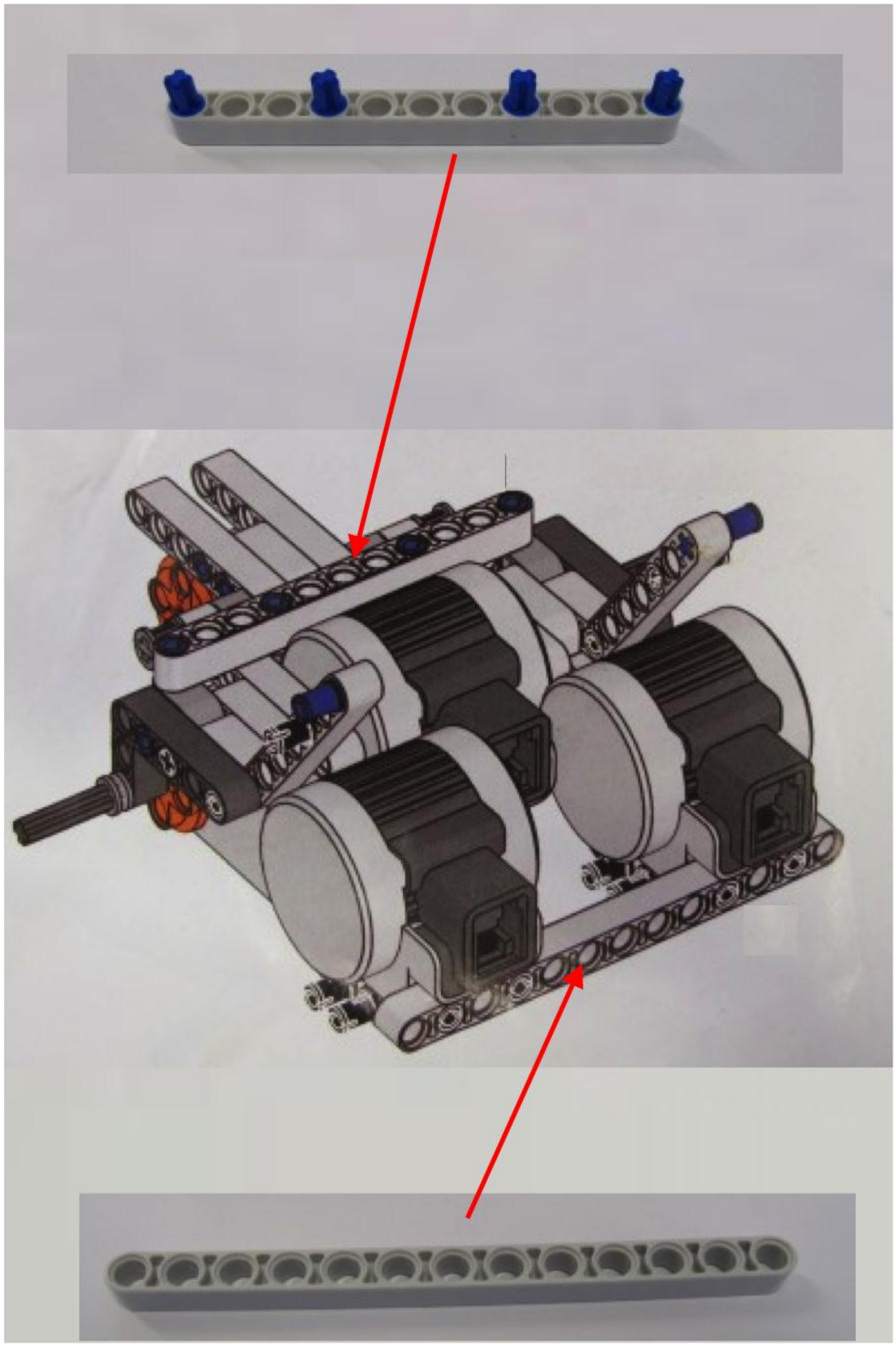

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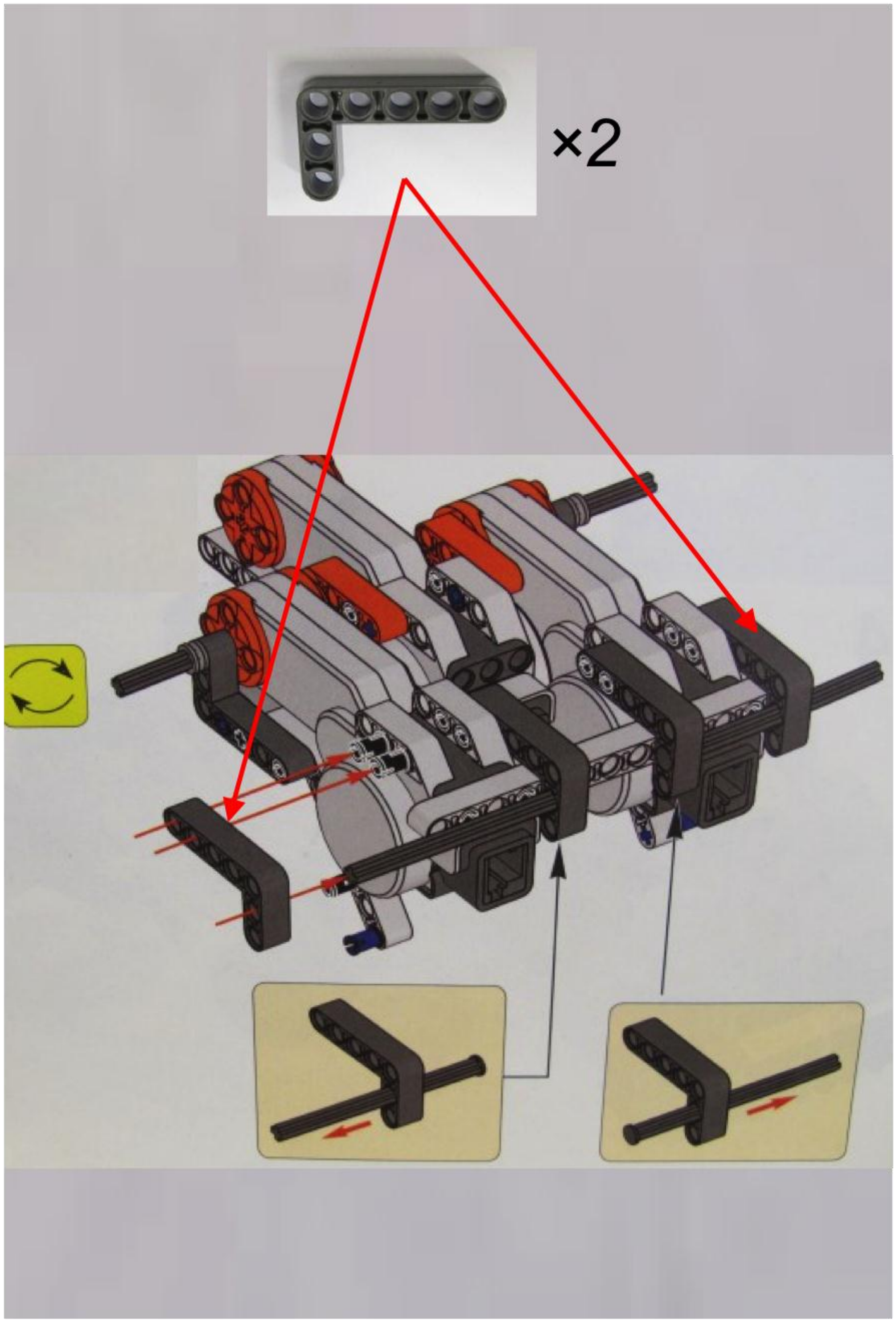

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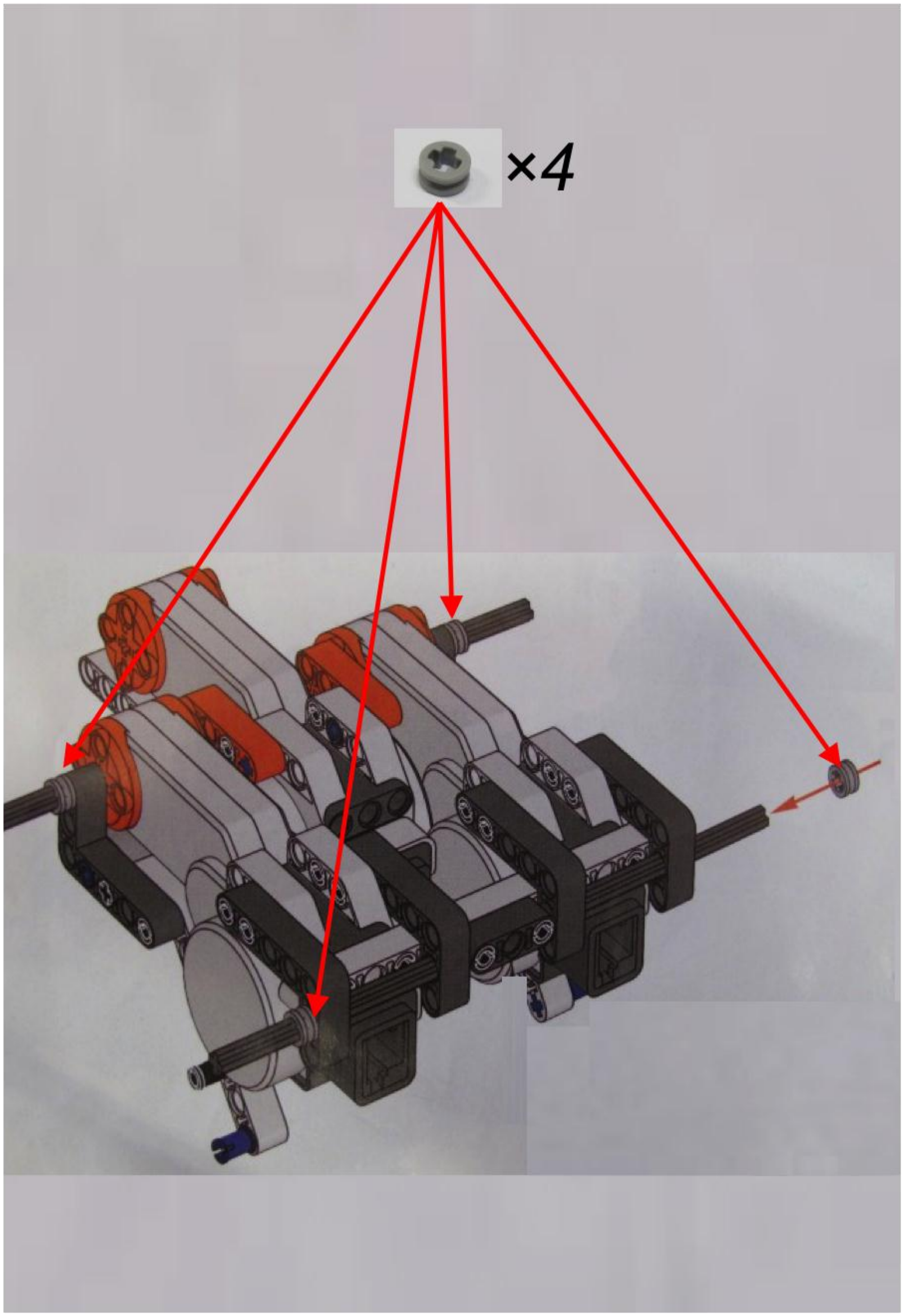

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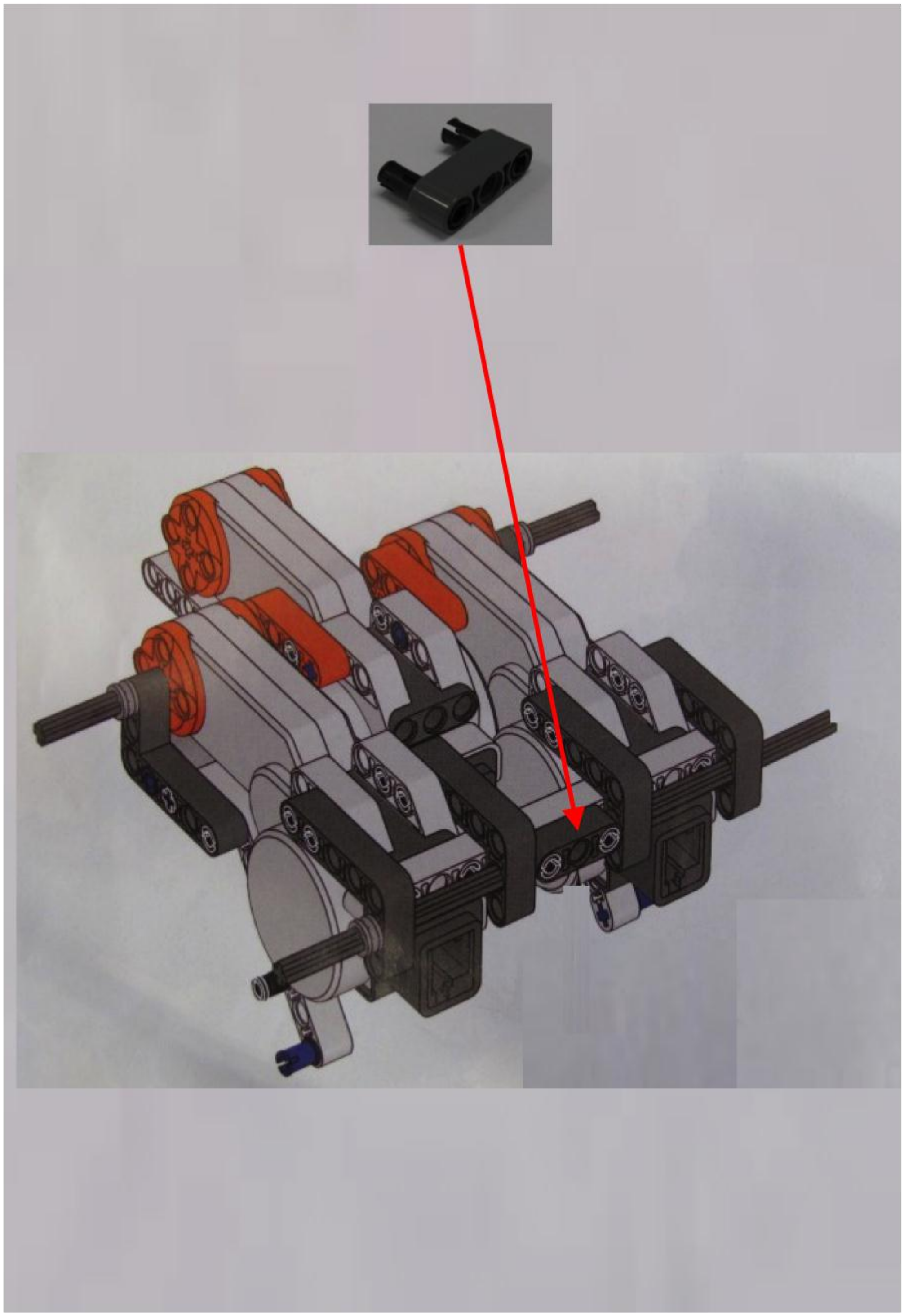

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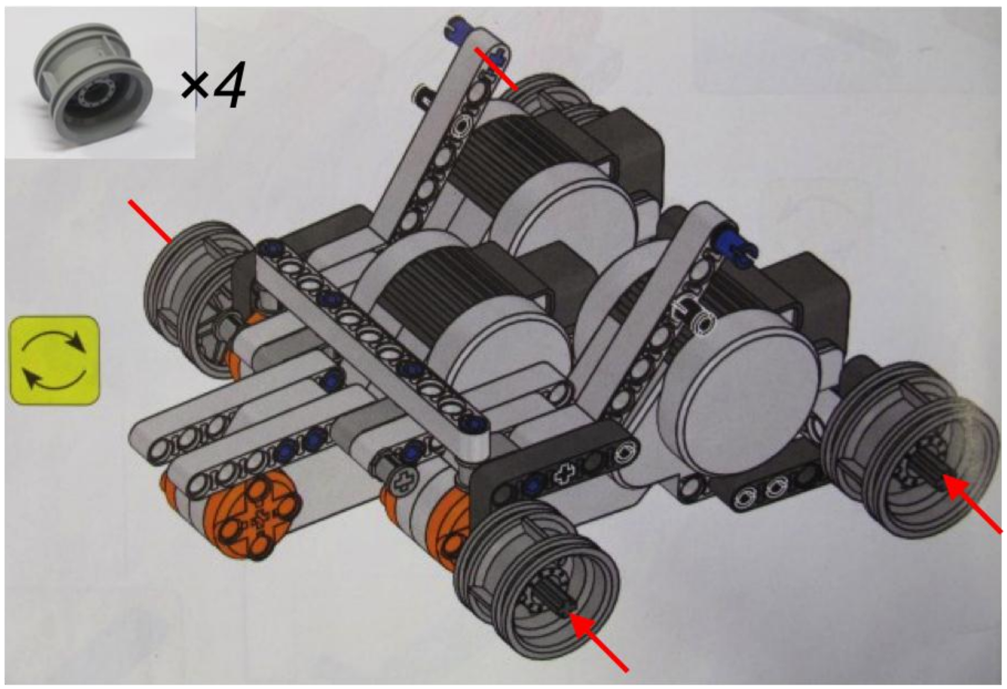

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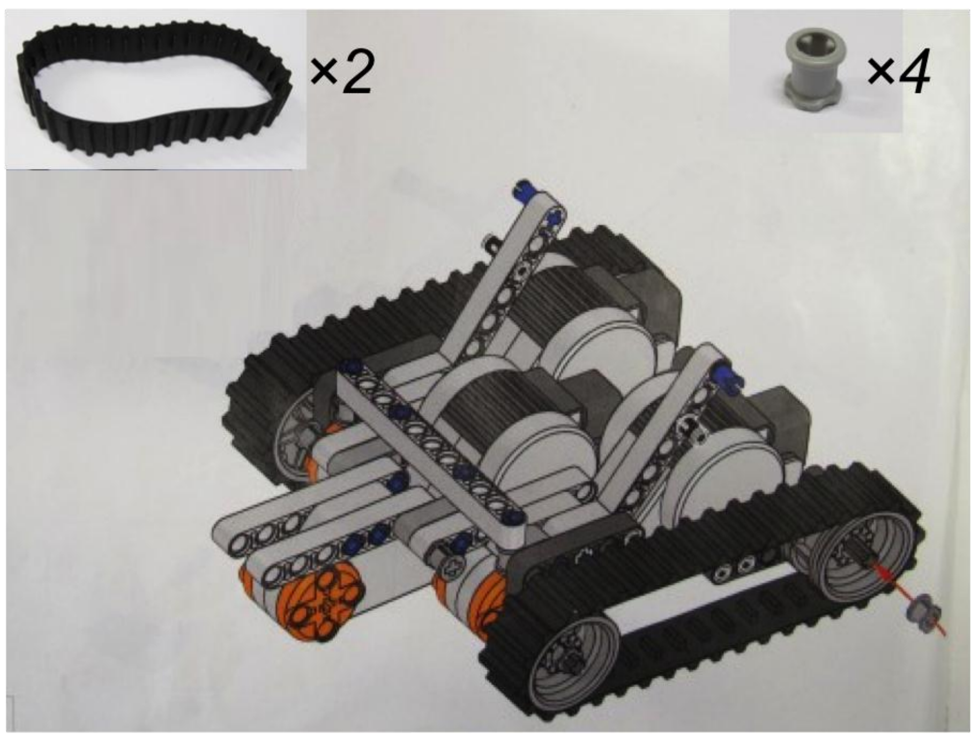

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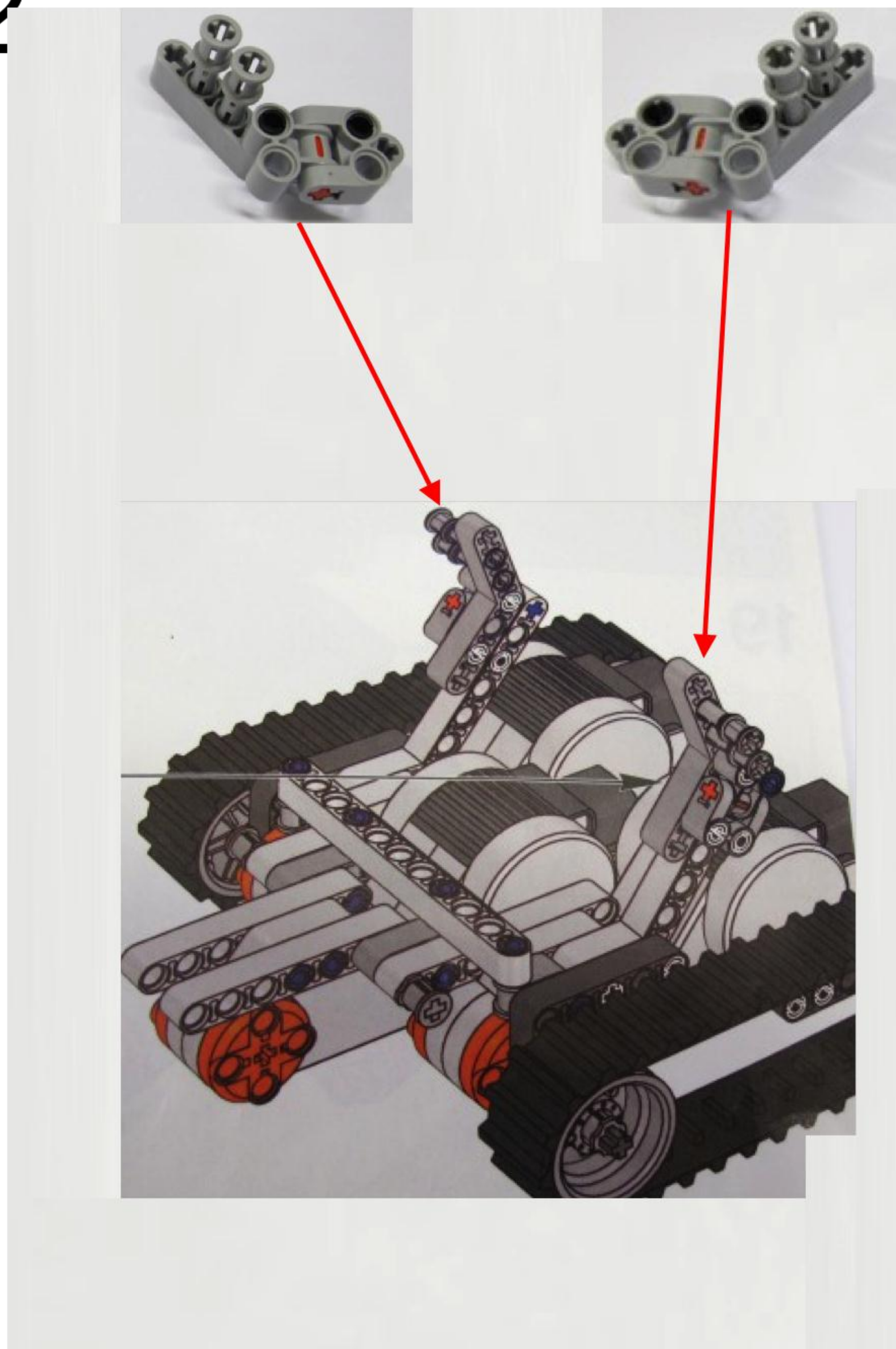

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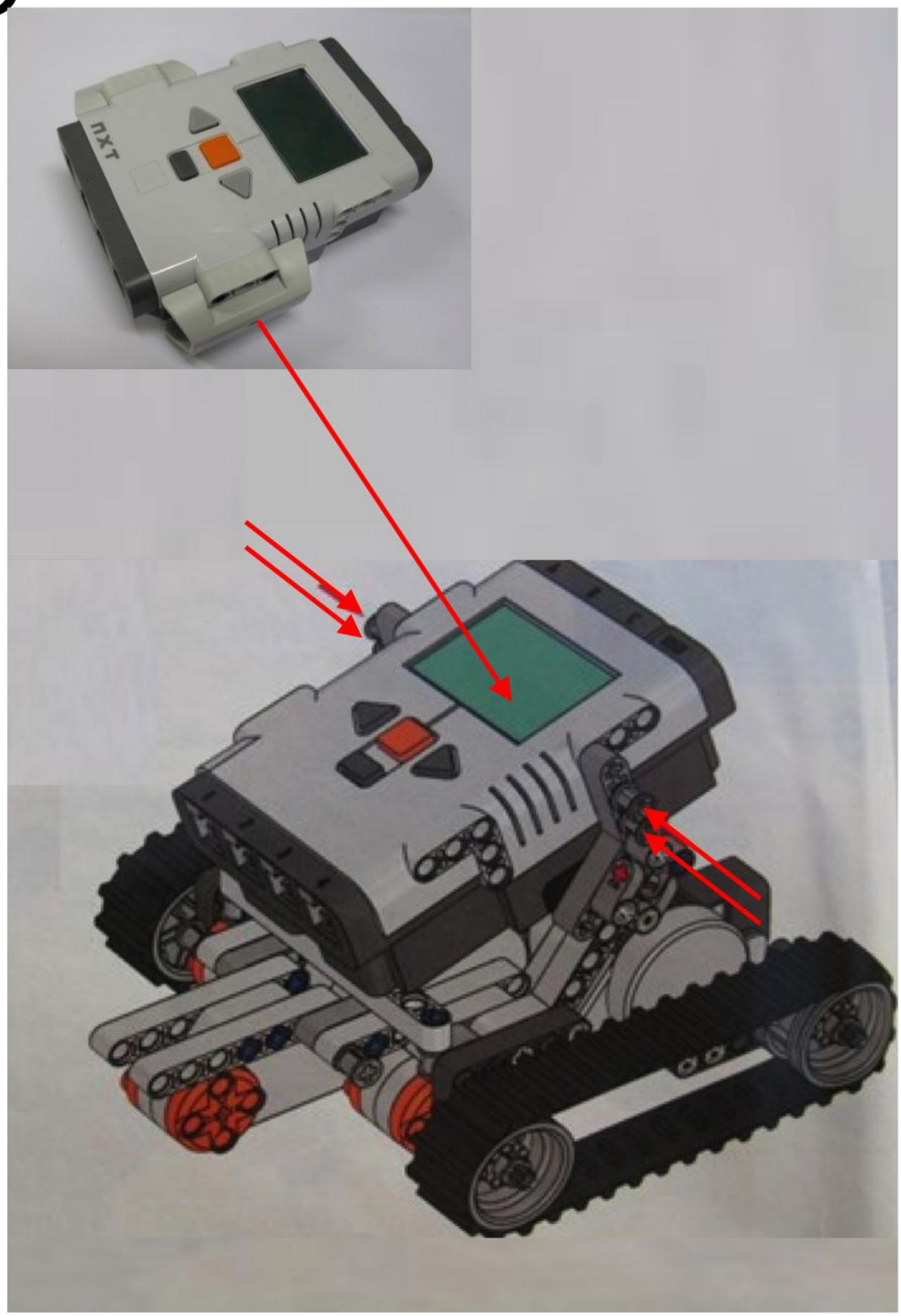
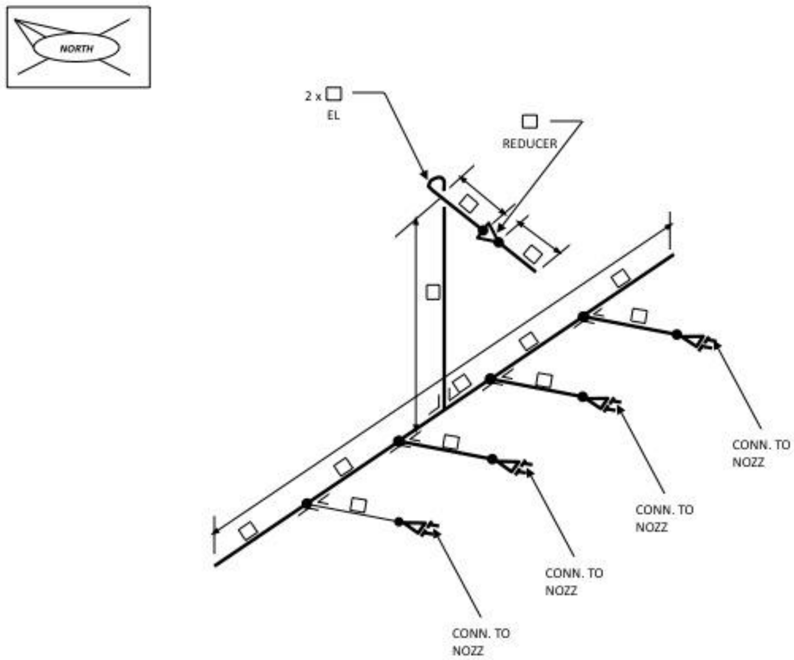


Appendix J: 2D Isometric Drawings for Assembling Piping System



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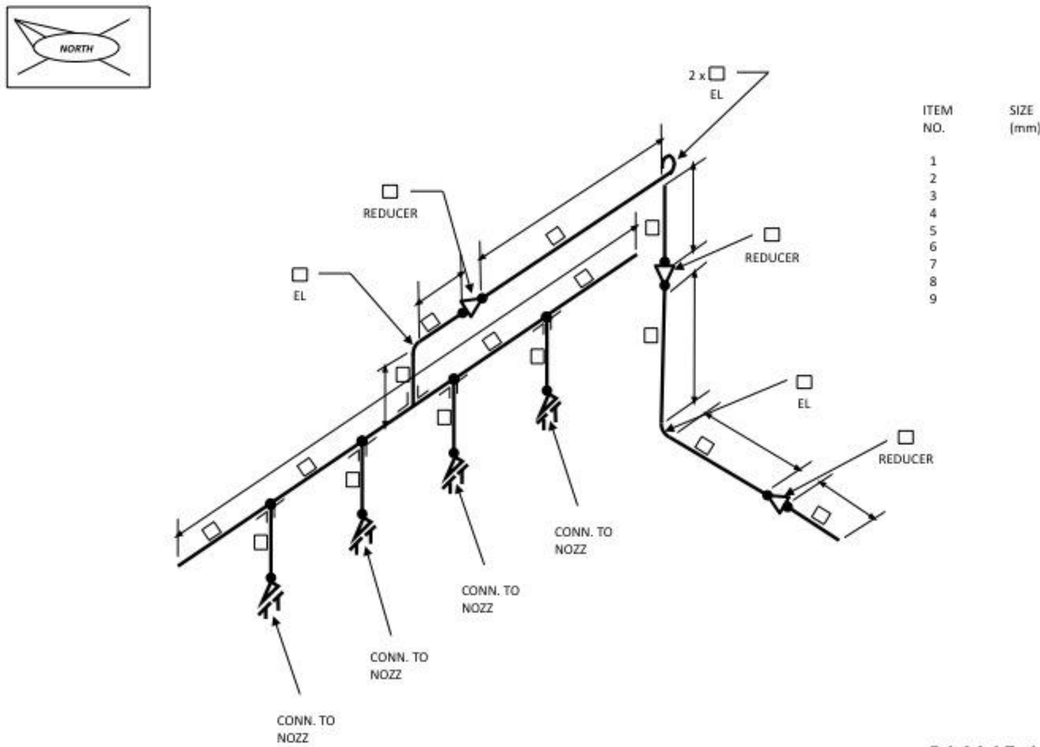
P14A06-1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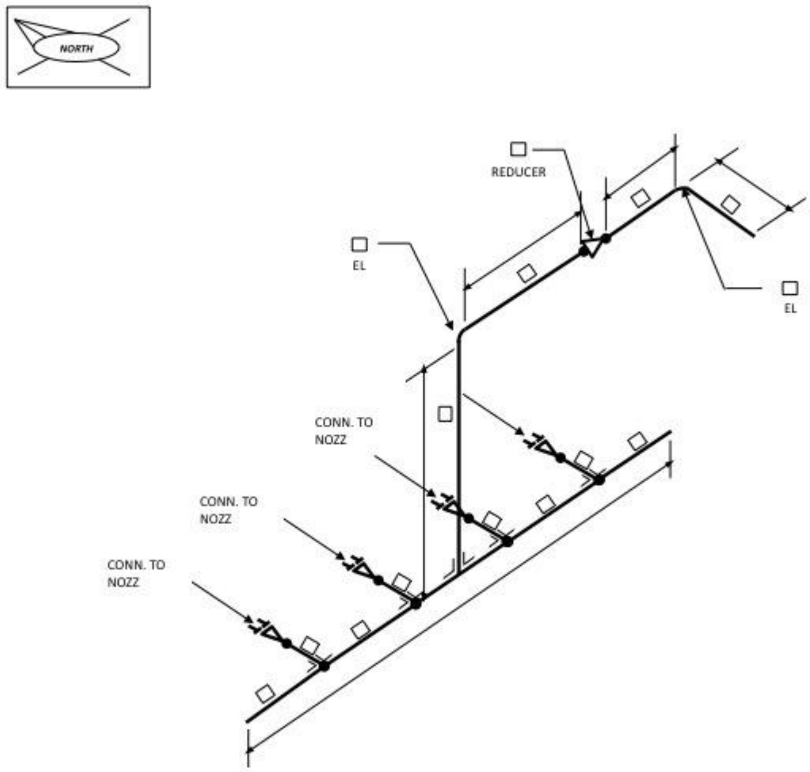
P14A15-1



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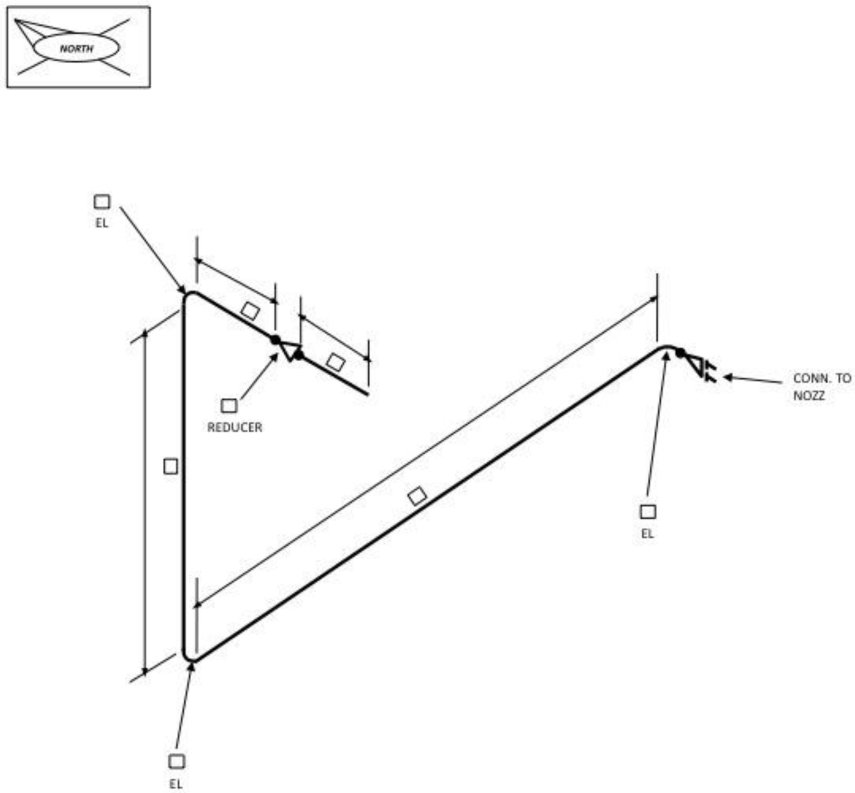

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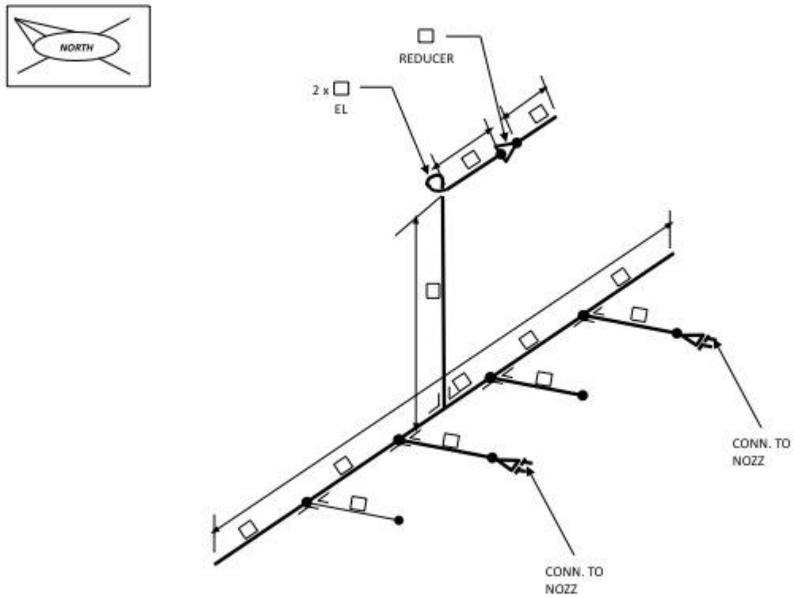

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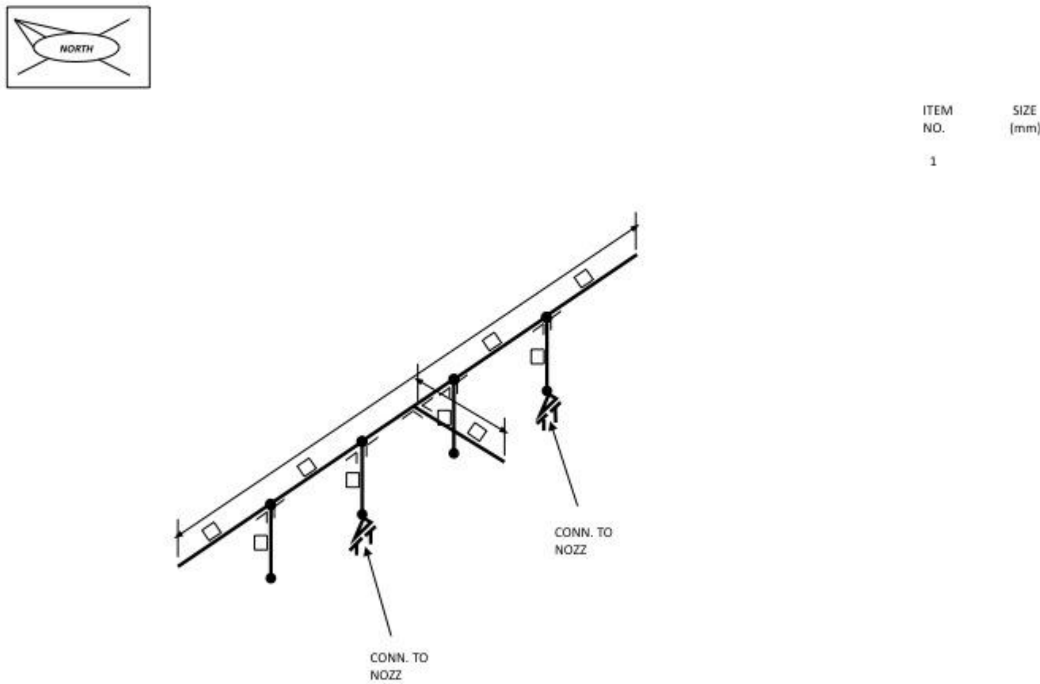

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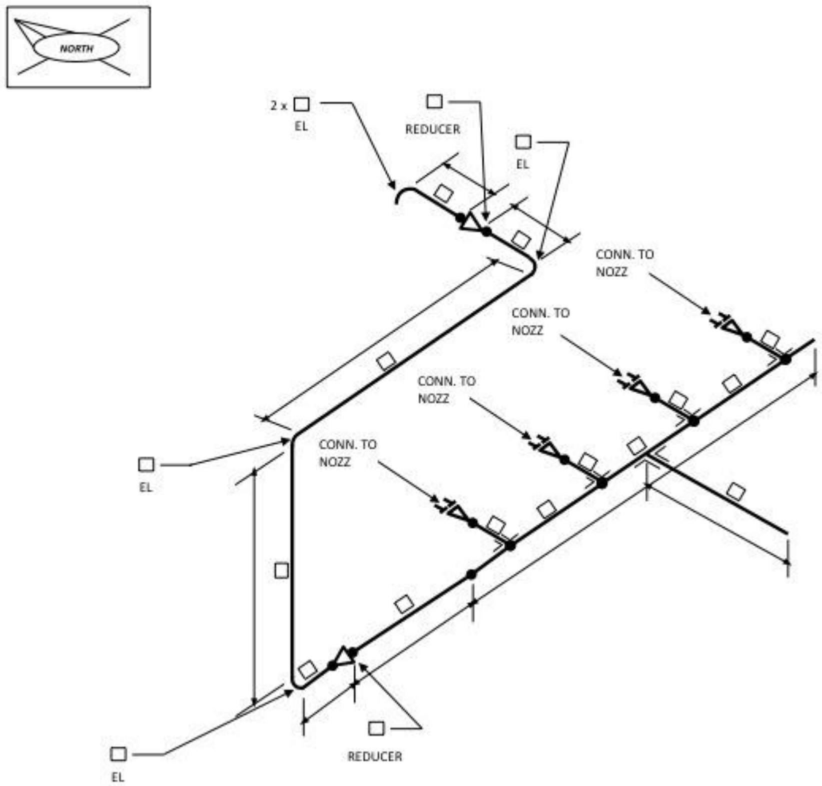

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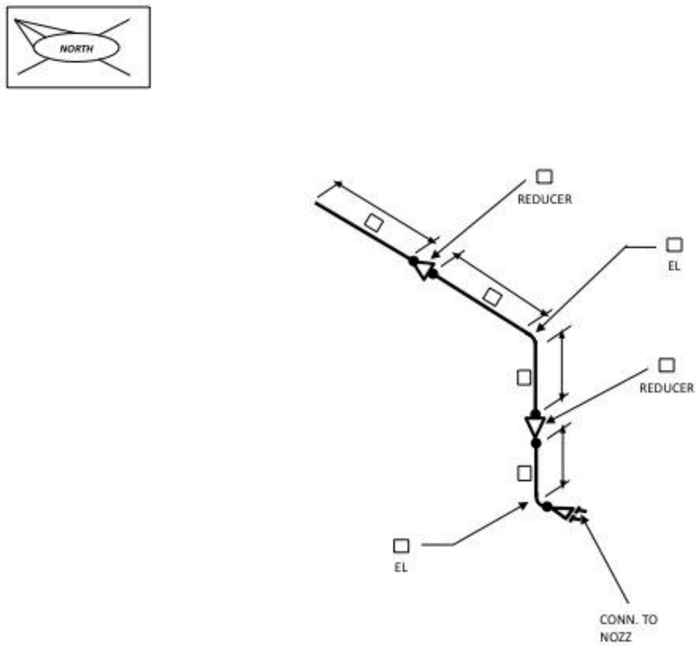

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P4

Appendix K: Post-Experiment Questionnaires Used in Scenario 1 and 3

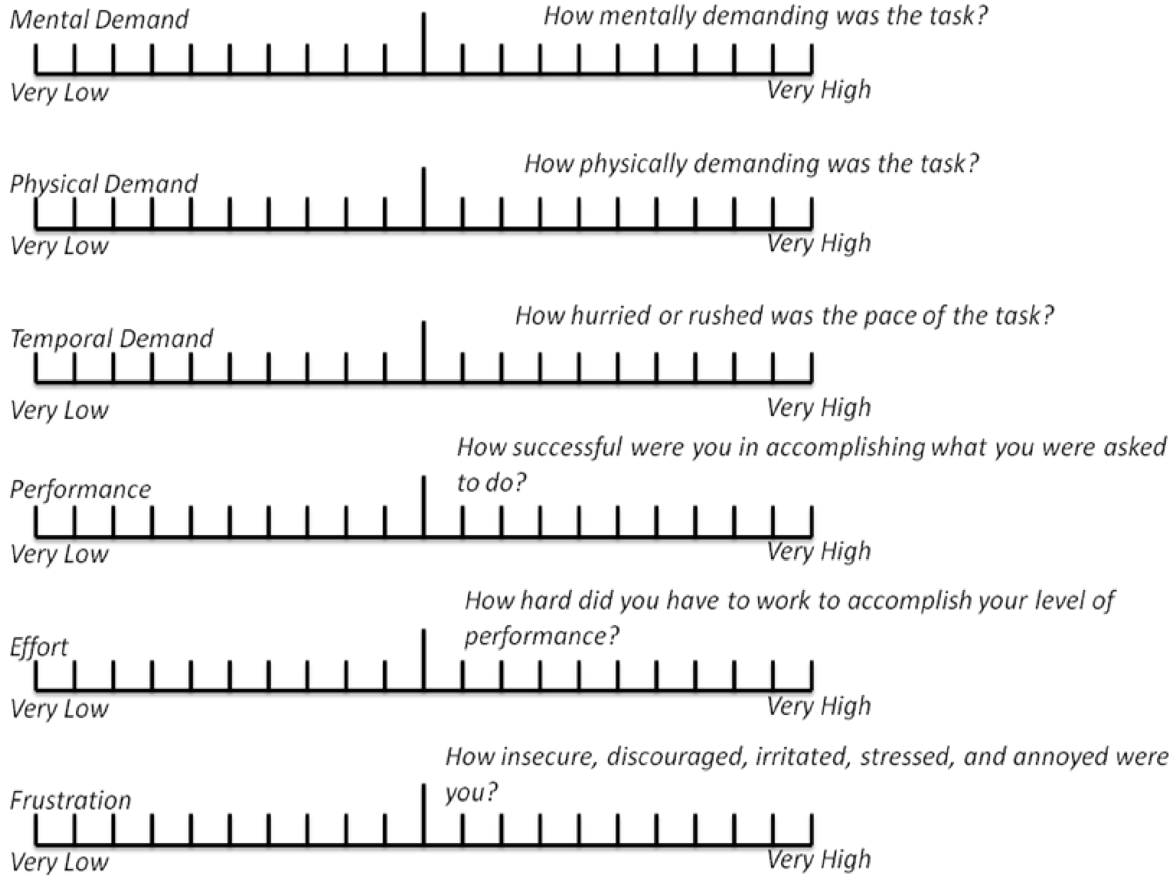
Project

Evaluating the Use of Augmented Reality to Facilitate Assembly

Below is for the participants

Age: *Gender:* *Area of Study:*

NASA Task Load Index:



QUESTIONNAIRE 1: Comparison of Use of 3D Manual Prints with AR System

Characterize your experience in the different assembly guidance, by ticking the appropriate box of the 7-point scale, in accordance with the question content and descriptive labels. Please consider the entire scale when making your responses, as intermediate levels may apply.

1. How was the quality of two means of visual guidance?

extremely bad *borderline* *extremely good*

	1	2	3	4	5	6	7
AR							
Manual							

Please provide comments:

2. **How was the mental burden of understanding two means of visual guidance?**

extremely hard *borderline* *extremely easy*

	1	2	3	4	5	6	7
AR							
Manual							

3. How easily did you acquire the spatial awareness of LEGO structure under two means?

extremely hard *borderline* extremely easy

	1	2	3	4	5	6	7
AR							
Manual							

4. How was the physical comfort of two behaviours: AR-based comparison and manual-based measurement?

uncomfortable *borderline* *comfortable*

	1	2	3	4	5	6	7
AR							
Manual							

5. **How did you think you were involved or immersed in two means?**

not involved *borderline* *completely engrossed*

	1	2	3	4	5	6	7
AR							
Manual							

6. **How did you think when you navigated in manual prints or AR system?**

annoying *I don't care* *pleased*

	1	2	3	4	5	6	7
AR							
Manual							

7. **When making decisions of pipe orientating and positioning, how much confidence or trust did you have on two means?**

I don't trust it *neutral* *I fully trust*

	1	2	3	4	5	6	7
AR							
Manual							

8. **How likely would you keep on using this guidance?**

definitely not *borderline* *definitely yes*

	1	2	3	4	5	6	7
AR							
Manual							

Please write down any comments, suggestions and feelings of interest.

QUESTIONNAIRE 2: Evaluation for AR system Relative to Manual Prints

The following deals with the evaluation of one method against the other method in five aspects. In order to minimise the section's bias and/or order effects to affect the results, we counterbalanced whether the animated AR system is evaluated relative to paper drawing.

1. **I felt that 3D structure presentation in the animated AR system aided understanding.**
   (I felt that 3D structure presentation in manual prints aided understanding)

   Totally agree ☐ ☐ ☐ ☐ *Totally disagree*

2. **Compared with manual prints, comparing dimension via display of the animated AR system was more convenient.**
   (Compared with the animated AR system, measuring dimension based on manual prints was more convenient)

   Totally agree ☐ ☐ ☐ ☐ *Totally disagree*

3. **The animated AR system increased the overall quality of output from the screen view. (The manual prints increased the overall quality of output from the paper view)**

Totally agree ☐ ☐ ☐ ☐ *Totally disagree*

4. **The animated AR system better facilitated the quantity of assembly work I could complete in a given amount of time.**
   (The manual prints better facilitated the quantity of assembly work I could complete in a given amount of time)

Totally agree ☐ ☐ ☐ ☐ *Totally disagree*

5. **The animated AR system increased my satisfaction with the outcome of the collaboration. (The manual prints increased my satisfaction with the outcome of the collaboration)**

Totally agree ☐ ☐ ☐ ☐ *Totally disagree*

Appendix L: Post-Experiment Questionnaires Used in Scenario 2

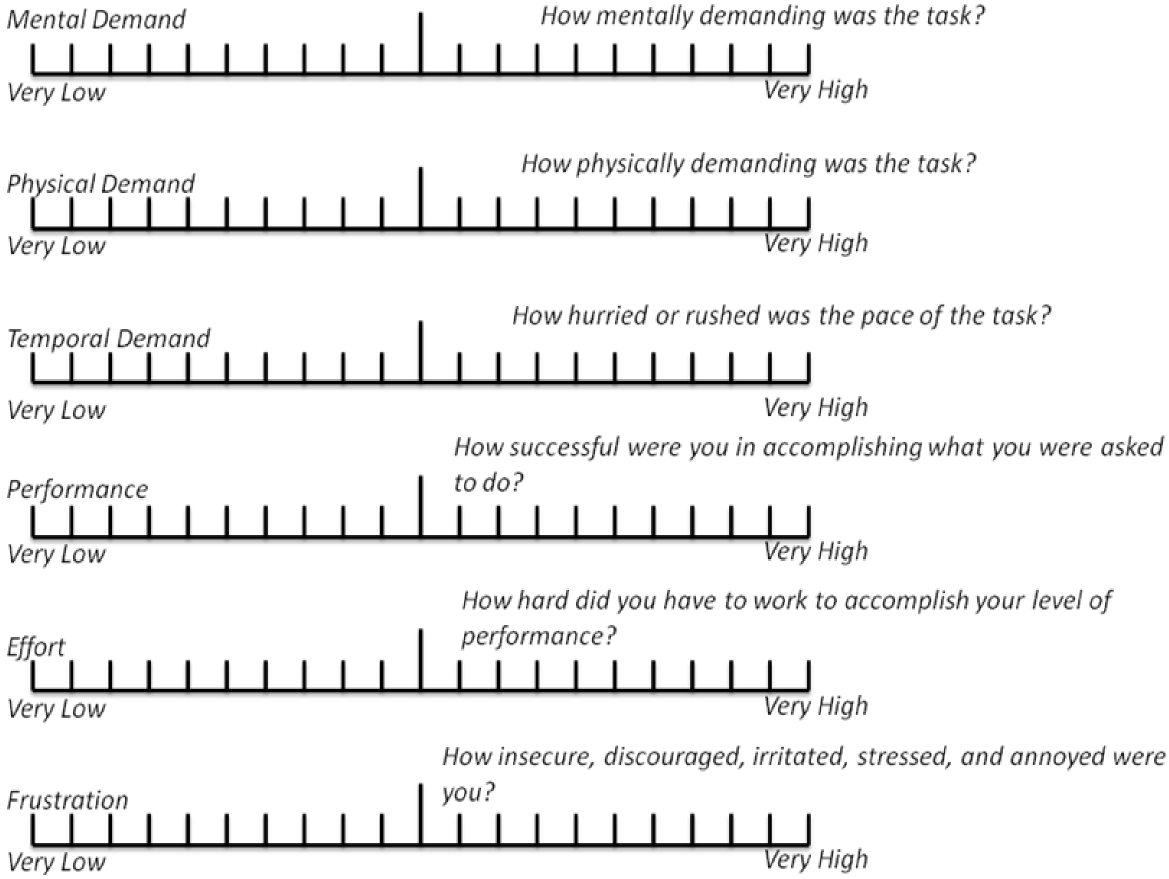
Project

Evaluating the Use of Augmented Reality to Facilitate Assembly

Below is for the participants

Age: *Gender:* *Area of Study:*

NASA Task Load Index:



QUESTIONNAIRE 1: Comparison of Use of 2D Isometric Drawings with AR System

Characterize your experience in the different assembly guidance, by ticking the appropriate box of the 7-point scale, in accordance with the question content and descriptive labels. Please consider the entire scale when making your responses, as intermediate levels may apply.

1. How was the quality of two means of visual guidance?

extremely bad *borderline* *extremely good*

	1	2	3	4	5	6	7
AR							
Drawing							

Please provide comments:

2. **How was the mental burden of understanding two means of visual guidance?**

extremely hard *borderline* *extremely easy*

	1	2	3	4	5	6	7
AR							
Drawing							

3. How easily did you acquire the spatial awareness of pipe structure under two means?

extremely hard *borderline* extremely easy

	1	2	3	4	5	6	7
AR							
Drawing							

4. How was the physical comfort of two behaviours: AR-based length comparison and drawing-based measurement?

uncomfortable *borderline* *comfortable*

	1	2	3	4	5	6	7
AR							
Drawing							

5. **How did you think you were involved or immersed in two means?**

not involved *borderline* *completely engrossed*

	1	2	3	4	5	6	7
AR							
Drawing							

6. **How did you think when you navigated in drawings or AR system?**

annoying *I don’t care* *pleased*

	1	2	3	4	5	6	7
AR							
Drawing							

7. **When making decisions of orientating and positioning, how much confidence or trust did you have on two means?**

I don't trust it *neutral* *I fully trust*

	1	2	3	4	5	6	7
AR							
Drawing							

8. **How likely would you keep on using this guidance?**

definitely not *borderline* *definitely yes*

	1	2	3	4	5	6	7
AR							
Drawing							

Please write down any comments, suggestions and feelings of interest.

QUESTIONNAIRE 2: Evaluation for AR system Relative to Isometric Drawings

The following deals with the evaluation of one method against the other method in five aspects. In order to minimise the section's bias and/or order effects to affect the results, we counterbalanced whether the animated AR system is evaluated relative to paper drawings.

1. **I felt 3D pipe structure presentation in the animated AR system aided understanding. (I felt that isometric pipe structure presentation in drawings aided understanding)**

Totally agree ☐ ☐ ☐ ☐ *Totally disagree*

2. **Compared with drawings, comparing pipe dimension via display of the animated AR system was more convenient. (Compared with the animated AR system, measuring the pipe based on scales in drawings was more convenient)**

Totally agree ☐ ☐ ☐ ☐ *Totally disagree*

3. **The animated AR system increased the overall quality of output from the screen view. (The drawings increased the overall quality of output from the paper view)**

Totally agree ☐ ☐ ☐ ☐ *Totally disagree*

4. **The animated AR system better facilitated the quantity of assembly work and I could complete in a given amount of time.**
(The isometric drawings better facilitated the quantity of assembly work and I could complete in a given amount of time)

Totally agree ☐ ☐ ☐ ☐ *Totally disagree*

5. **The animated AR system increased my satisfaction with the outcome of the collaboration. (The isometric drawings increased my satisfaction with the outcome of the collaboration)**

Totally agree ☐ ☐ ☐ ☐ *Totally disagree*

Appendix M: Useability Evaluation of the Animated AR system

Navigation:

1. **Did you often feel disoriented?**

   (very little) 1 2 3 4 5 6 7 (very much)

2. **Did the surrounding real background help your spatial comprehension?**

   (very little) 1 2 3 4 5 6 7 (very much)

Input mechanism:

3. **Did you feel annoying or inconvenient when operating keyboard or marker to view different angles of virtual image?**

   (very little) 1 2 3 4 5 6 7 (very much)

Visual output (display):

4. **Did visual output have adequate stability of the image as you move with no perceivable distortions in visual images?**

   (very little) 1 2 3 4 5 6 7 (very much)

5. **Was the FOV (field of view) appropriate for supporting this activity?**

   (very little) 1 2 3 4 5 6 7 (very much)

6. **Did the monitor-based visual display create difficulties for observing?**

   (very little) 1 2 3 4 5 6 7 (very much)

7. **Did you believe the virtual images could be spatially matched with the physical counterparts?**

   (very little) 1 2 3 4 5 6 7 (very much)

8. **Was the AR display effective in conveying convincing scenes of models appearing as if in the real world?**

   (very little) 1 2 3 4 5 6 7 (very much)

Immersion:

9. **With the AR system, were you isolated from and not distracted by outside activities?**

   (very little) 1 2 3 4 5 6 7 (very much)

Comfort:

10. Was the AR system comfortable for long-term use?

(very little) 1 2 3 4 5 6 7 (very much)

Please provide comments:

11. Did you experience excessive eye fatigue?

(very little) 1 2 3 4 5 6 7 (very much)

12. Did you experience high levels of general discomfort during interaction with the AR system?

(very little) 1 2 3 4 5 6 7 (very much)

Aftereffect:

13. Did you experience any of the following after exposure to the AR system: "blurred vision"; "dizziness"; "nausea"; "difficulty focusing"; "loss of vertical orientation"?

(Yes / No)

If yes, please specify:

14. **Would you embrace the opportunity to user the AR system again in the future?**

(Yes / No)

Appendix N: Raw Data for Task Performance in Experiment I

The statistics of raw data for scenario 1 and 2 of experiment I was presented in Figures 25, 26, 31 and 33, and in Tables 7, 13, 14 and 15.

Appendix O: Raw Data for Task Performance in Experiment II

Trainees	Elapsed time	Errors (9th & Time)	Elapsed time	Errors (9th & Time)	Elapsed time	Errors (9th & Time)	Elapsed time	Errors (9th & Time)
1 (11) (F)	11 mins	4 (no, 90s)	7 mins	0 (no, 66s)				
2 (8) (F)	15 mins	2 (yes, 166s)	8 mins	0 (no, 45s)				
3 (10) (F)	14 mins	3 (yes, 112s)	7 mins	1 (no, 67s)	6 mins	0 (no, 30s)		
4 (13) (M)	10 mins	2 (no, 98s)	7 mins	0 (no, 45s)				
5 (8) (M)	8 mins	3 (yes, 70s)	6 mins	0 (no, 65s)				
6 (6) (F)	16mins	6 (yes, 183s)	14 mins	4 (yes, 62s)	10 mins	0 (no, 68s)		
7 (14) (M)	20 mins	5 (yes, 238s)	14 mins	3 (yes, 88s)	10 mins	0 (no, 67s)		
8 (11) (F)	16 mins	4 (yes, 140s)	9 mins	0 (no, 65s)				
9 (8) (M)	17 mins	7(yes, 188s)	9 mins	3 (no, 105s)	6 mins	0 (no, 55s)		
10 (13) (F)	7 mins	1 (no, 40s)	7 mins	0 (no, 40s)				
11(13) (M)	12 mins	3 (no, 77s)	8 mins	0 (no, 67s)				
12 (8) (F)	12 mins	5 (yes, 102s)	12 mins	3 (yes, 88s)	7 mins	0 (no, 68s)		
13 (15) (M)	10 mins	3 (no, 140s)	7 mins	0 (no, 50s)				
14 (13) (M)	15 mins	3 (yes, 180s)	8 mins	1 (no, 28s)	7 mins	0 (no, 33s)		
1 (11) (M)	18 mins	4 (no, 61s)	9 mins	1 (no, 33s)	8 mins	0 (no, 48s)		
2 (11) (M)	20 mins	5 (yes, 155s)	11 mins	2 (no, 66s)	8 mins	0 (no, 28s)		
3 (14) (M)	14 mins	4 (yes, 85s)	9 mins	3 (no, 44s)	6 mins	0 (no, 34s)		
4 (11) (M)	16 mins	7 (yes, 103s)	10 mins	4 (no, 51s)	9 mins	1 (no, 40s)	6 mins	0 (no, 20s)
5 (11) (M)	17 mins	6 (yes, 78s)	13 mins	4 (yes, 45s)	10 mins	1 (no, 31s)	7 mins	0 (no, 21s)
6 (13) (F)	18 mins	7 (yes, 133s)	13 mins	5 (yes, 41s)	12 mins	2 (yes, 30s)	10 mins	0 (no, 22s)
7 (14) (F)	20 mins	7 (yes, 112s)	17 mins	4 (yes, 67s)	10 mins	0 (no, 55s)		
8 (9) (F)	21 mins	8 (yes, 150s)	18 mins	5 (yes, 58s)	9 mins	2 (no, 25s)	9 mins	0 (no, 25s)
9 (14) (F)	25 mins	6 (yes, 140s)	9 mins	2 (no, 42s)	8 mins	0 (no, 40s)		
10 (13) (F)	20 mins	5 (yes, 122s)	15 mins	3 (yes, 78s)	12mins	0 (no, 30s)		
11 (8) (M)	18 mins	7 (yes, 212s)	14 mins	3 (yes, 180s)	10 mins	2 (no, 40s)	8 mins	0 (no, 20s)
12 (11) (F)	17 mins	6 (yes, 177s)	16 mins	4 (yes, 83s)	9 mins	1 (no, 37s)	7 mins	0 (no, 35s)
13 (14) (F)	20 mins	8 (yes, 188s)	12 mins	5 (yes, 98s)	10 mins	3 (no, 66s)	8 mins	0 (no, 30s)
14 (11) (M)	17 mins	6 (yes, 92s)	12 mins	2 (no, 88s)	9 mins	0 (no, 43s)		

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