# Using Animated Augmented Reality to Cognitively Guide Assembly

Lei Hou[1]; Xiangyu Wang[2]; Leonhard Bernold, M.ASCE[3]; and Peter E. D. Love[4]

**Abstract:** Assembly is the process in which two or more objects are joined together. An assembly manual is typically used to guide the tasks required to put together an artifact. As an emerging technology, augmented reality (AR) integrates three-dimensional (3D) images of virtual objects into a real-world workspace. The insertion of digitalized information into the real workspace using AR can provide workers with the means to implement correct assembly procedures with improved accuracy and reduce errors. A prototype animated AR system was configured for assembly tasks that are normally guided by reference to documentation and was tested using a series of experiments. A LEGO model was used as the assembly and experimental tester task. Experimentation was devised and conducted to validate the cognitive gains that can be derived from using AR to assemble a LEGO model. Two formal experiments with 50 participants were conducted to compare an animated AR system and the paper-based manual system. One experiment measured the cognitive workload of using the system for assembly, whereas the other measured the learning curves of novice assemblers. Findings from the experiments revealed that the animated AR system yielded shorter task completion times, less assembly errors, and lower total task load. The results also revealed that the learning curve of novice assemblers was reduced and task performance relevant to working memory was increased when using AR training. Future work will apply the knowledge gained from the controlled assembly experiments to the real-scale construction assembly scenario to measure the productivity improvements. **DOI:** 10.1061/(ASCE)CP.1943-5487.0000184. *© 2013 American Society of Civil Engineers.*

**CE Database subject headings:** Construction management; Productivity; Digital techniques; Imaging techniques.

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## Introduction

Assembly is the process in which two or more objects are joined together. An assembly manual is typically used to guide the tasks required to put together an artifact. A well-formulated assembly manual should possess the following assembly information: visual perspectives of product components/parts, parameters or dimensions, technical requirements in quality, installation and testing specifications, and other auxiliary information.

The implementation of an assembly task typically consists of work and nonworkpiece-related activities (Neumann and Majoros 1998). In each assembly step, the assembler is required to conduct a series of physical operations (e.g., observing, grasping, installing) and mentally manual-related processes (comprehending, translating, and retrieving information context) (Neumann and Majoros 1998). Neumann and Majoros (1998) also suggested that information-related activities tend to be cognitive, whereas workpiece-related activities are kinesthetic and psychomotor. Zaeh and Wiesbeck (2008) suggested that assembly using a manual is a time-consuming process. Moreover, Zaeh and Wiesbeck (2008) suggested that the process of assembly based on a planar manual fails to consider the cognitive issues and the large number of switchovers between physical (workpiece-related) and mental (manual-related) processes, which can result in operational suspensions and attentional transitions occurring in novice assemblers. The time-consuming nature of activities has also been identified by Towne (1985), who found that information-related activities (cognitive workload) accounted for 50% of the total task workload. Similarly, Veinott and Kanki (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. Neumann and Majoros (1998) identified that individual technicians differed significantly in how much time they devoted to cognitive/informational tasks, but demonstrated marginal differences with respect to operational tasks. The use of an assembly manual for complex and intricate processes can contribute mental tiredness and the propensity to commit errors because information retrieval often increases (Watson et al. 2008). Likewise, Veinott and Kanki (1995) revealed that 60% of the errors that are committed are procedural and are attributable to misunderstanding the manual. Such misunderstanding may arise because of the unilateral retrieval of information, which may trigger behavioral repetition and therefore suppresses motivation (Wang and Dunston 2008).

An assembly manual is typically paper-based and contains a large quantity of information pertaining to product parts/components, a large amount of which may be redundant and interminable, especially for complex tasks. As a result, this can potentially hinder an assembler's information orientation and his/her ability to understand complex assembly relations. It is widely

[1]Postgraduate, Faculty of Built Environment, Univ. of New South Wales, Sydney, NSW 2052, Australia. E-mail: houleilei@yeah.net

[2]Professor, School of Built Environment, Curtin Univ., GPO Box U1987, Perth, WA 6845, Australia; and International Scholar, Dept. of Housing and Interior Design, Kyung Hee Univ., Korea (corresponding author). E-mail: xaingyu.wang@curtin.edu.au

[3]Associated Professor, School of Civil and Environmental Engineering, Univ. of New South Wales, Sydney, NSW 2052, Australia. E-mail: leonhard.bernold@gmail.com

[4]John Curtin Distinguished Professor, School of Built Environment, Curtin Univ., GPO Box U1987, Perth, WA 6845, Australia. E-mail: p.love@curtin.edu.au

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accepted that the capacity of selective information retrieval and filtering does not occur until assembly experiences and expertise are acquired, and therefore extra-targeted training activities may sometimes be needed (Agrawala et al. 2003). Using an assembly manual does not necessarily provide an assembler with the problem-solving skills that are often required when putting together components (Pastora and Ferrera 2009). It often takes months or even years for a novice to develop expert knowledge of the assembly processes, particularly those of a complex nature (Hoffman et al. 1998). In some cases, an expert assembler must constantly refer to an assembly manual for unfamiliar procedures or procedures that are deemed to be arduous. Aside from movements such as picking, comparing, grasping, rotating, connecting, and fixing the to-be-assembled components, assemblers have to undertake several nonassembly-related kinetic operations to understand the assembly process by paging up/down, head swivelling, and comparing various elevations.

In construction, assembly is a process in which workers refer to technical specifications (information activity) to obtain the right information (information activity), identify components (workpiece activity), place the component, compare standards (workpiece activity), and then make a judgment of its correctness (if necessary, rework may be required). The entire process is iterative and repeated, and a learning process is triggered that 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 labor intensive and therefore increase 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 associated with assembly in construction:

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 in which assembly problems may arise occurs during the installation of heating, ventilation, and air-conditioning (HVAC) piping. Workers are required to measure the available installation and workspace, read from the technical drawings, find and identify the right pipe component, decide its appropriateness, install, and then check its correctness. Similarly, the rebar assembly process usually takes place in a prefabricated shop prior to being delivered to the site. Workers spend a considerable amount of time trying to find the right length and diameter of rebar to install. The assembly sequence is critical because the incorrect placement of rebar can inhibit access to space inside a welded cage. Workers usually read rebar plans, find the piece, place and weld it, and then check its correctness. An efficient way to identify rebar is through color coding with different flags to differentiate its size and type. This method, however, does not address the assembly sequence that is adopted.

The insertion of digitalized information into the real workspace using augmented reality (AR) can provide workers with the means to implement correct assembly procedures with improved accuracy (Wang and Dunston 2006a, b). With this in mind, this paper designs and develops 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 is tested using a series of experiments. The proposed system can facilitate the transition from paper-based manual systems (information activity) to workpiece activity by complementing human associative information processing and memory. The paper particularly focuses on the cognitive aspects associated with AR and assembly.

## From Virtual to Augmented Reality

Virtual reality (VR) has been used extensively to facilitate the assembly of products (Ritchie et al. 2007). Product designers are able to create virtual prototypes for accessories, modules, and parts in virtual environments (VE). Trial assembly in a virtual environment enables problematic tasks to be identified and various assembly methods to be explored. Commercial VE prototyping software such as computer-aided design (CAD), Pro/Engineer, and Catia has been widely used to facilitate the product assembly and design process. Product technicians are capable of designing and developing various accessories, modules, and parts with different functions and dimensions and conducting assembly guidance in a virtual space. Regardless of the accuracy that can be acquired from using VR for product assembly, errors and defects can still arise.

Virtual reality attempts to replace a user's perception of the surrounding world with a computer-generated artificial three-dimensional (3D) VE. However, a VE is unable to account for the diverse interferences such as weather, labor constraints, and schedule pressure that 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 because of a lack of sensory feedback and are therefore unable to accommodate for perceptual and cognitive viewpoints (Wang and Dunston 2006a, b). The lack of interaction between the virtual and real world hinders the adoption of VR to product assembly tasks.

Augmented reality has been identified as a solution to addressing the problem between virtual and real entities (Azuma et al. 2001). As an emerging technology, AR integrates images of virtual objects into a 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 a virtual prototyping with real entities. This gives a virtual world an ameliorated connection to the real world while maintaining the flexibility of the virtual world. Whereas 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 virtual components while identifying potential interferences between the to-be-assembled and existing objects inside the real environment. Therefore, in AR environment, an assembler can not only interact with real environments, but also interact with augmented environments (AE) that are structured to offset the partial sensory loss that may be acquired within VR. Furthermore, to improve the feedback of augmentation, additional nonsituated elements could be added into the assembly process such as voice recordings, animation, and video.

Augmented reality has been identified as a key technology that can be used to improve the product assembly process because it can take into account human cognition (Salonen et al. 2007). For example, Salonen et al. (2007) used a multimodality system based on a head-mounted display (HMD), a marker-based software toolkit (AR Toolkit), image tracking cameras, web cameras, and a microphone to examine industrial product assembly. Xu et al. (2008) developed a markerless-based registration technology to overcome the inconveniences of applying markers as carriers in the assembly design process. Augmented reality technology has also been used extensively in the assembly design of a wide range



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of products, e.g., furniture (Zauner et al. 2003), toys (Tang et al. 2003), and industrial robots (Yamada and Takata 2002). Although such studies have made a significant contribution to understanding the product assembly process, several key issues remain unresolved within the assembly domain. For example, researchers have yet to acquire an in-depth understanding of an assemblers' 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 therefore do not take into their 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 their 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. As a result, it is envisaged that a higher degree of integration between the information retrieval processes and task operations can be achieved. This is in stark contrast with the manual system in which assembly typically needs to be conducted between retrieving and interpreting information, selecting the component to be assembled, and putting together components. The use of AR enables the to-be-assembled components to be placed at designated workspaces by following the virtual and the animated pathways identified from a HMD or on a computer screen (Fig. 1). 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 (workpiece stocking area) and assembly point. Furthermore, an animated AR system is able to predefine the tasks required (including noninterfered assembly paths) by an assembler so they can readily follow the process to be considered.

## Animated AR System

An animated AR system for improving the construction assembly process that utilizes marker registration technology and visualization is developed and presented. The proposed system for assembly provides information about components to be mounted and outputs to be assembled step-by-step so that an assembler can monitor their progress and ensure they do not damage components that have already been installed. The proposed prototype involves the traditional establishment and implementation of an AR, which includes a computer monitor, predefined paper-based markers, interactive computer graphics modeling, animation and rendering software (3DSMAX), an ARToolkit, and an attached OpenGL. Using the ARToolkit, virtual images of product components can be registered onto predefined markers and captured in view of monitors using HMD or a computer screen using a marker tracking camera.

The virtual counterparts of real entities are acquired from 3DSMAX and then plugged into the ARTookit through a graphical interface. The locomotion along the virtual assembly path for each virtual component and the method of assembly are registered to 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 textures, weight, color, and specification.

### Hardware Establishment

The hardware setup of the animated AR system is depicted in Fig. 2, and the details are described subsequently.

**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 sustain 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 facilitate their operations from various positions.

**Position of Monitor and Manual**

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

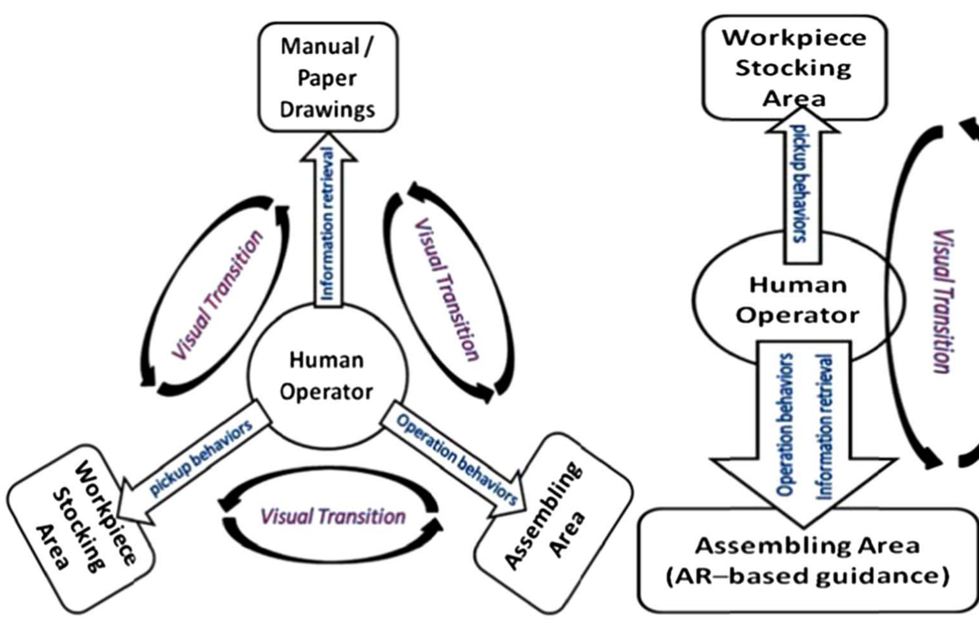


**Fig. 1.** Visual transition between the manual guidance and the animated AR system

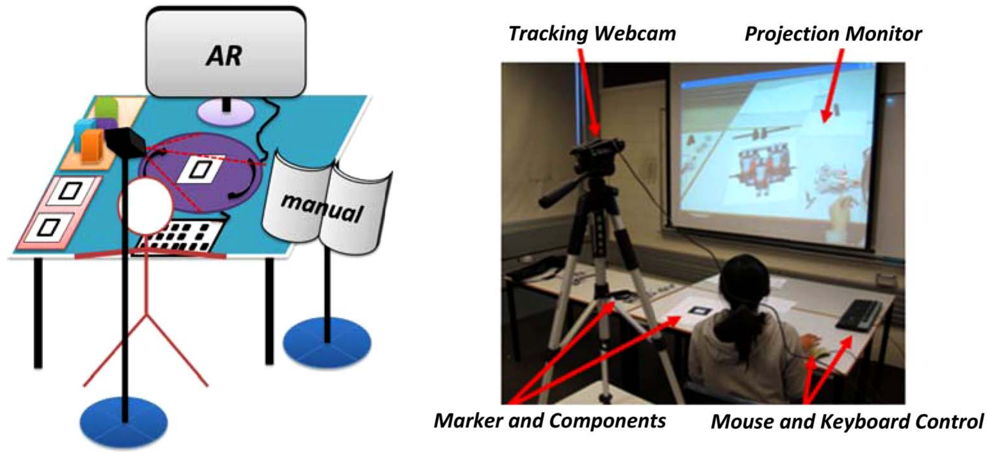


**Fig. 2.** Hardware setup and real layouts of model assembly

visual transition when implementing the assembly task. A mouse and keyboard provide assemblers with easy control of the animation course because they can play, pause, and replay the animation and 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. Planar information for assembly guidance can be retrieved by the animated AR because it is based on the manual's procedures. The manual is positioned on the right of the workbench, braced by a bracket. When implementing the LEGO model assembly task or training task, assemblers are coerced to frequently switch their attention between workbench and manual and page up or page down to retrieve information.

**Tracking Webcam**

The tracking webcam is a Logitech Webcam Pro 9000 HD, which can ensure a high-definition (HD) view with an autofocus. It projects to the rotatable workbench to overlap the webcam view and participants' field of vision. The images of virtual components and the real components are captured by the webcam so the assemblers are required to only focus on the augmenting scene identified on the monitor.

By tracking the predefined markers, the customized animated guidance can be displayed on the monitor. The angle between the webcam projection and the horizontal workbench is fixed in this instance, but this is only to ensure that the webcam is able to capture the black frame of the marker and the assemblers' manipulation.

**Paper-Based Markers and Components**

Markers are all trained using the ARToolkit. There is a main marker that is used to animate the process throughout the entire product assembly, and 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 to-be-assembled components. All markers are provisionally placed on the left of the workbench. Similarly, the to-be-assembled physical components are also placed on the left zone of the workbench, which is the workpiece stocking area, as depicted in Fig. 2.

## *Software Setup*

Conventional AR environments are based on the ARToolkit in which virtual objects are usually drawn using pure drawing functions of OpenGL (Open Graphics Library), a multiplatform high-level 3D graphics application programming interface (API). However, if users want to build their own models, they must acquire the knowledge of OpenGL. For the purpose of facilitating layman users without OpenGL knowledge, some AR systems have realized the direct loading of varieties of model files, such as BuildAR and Layer. The aforementioned systems cannot be customized to fit the experimental requirements of the research to be undertaken in this paper, specifically issues relating component dimensional comparisons and assembly clue registration. Thus, it was decided to redevelop a set of functionalities that can dynamically load model files into the proposed AR system. Akin to other AR systems, the proposed animated AR system is a user-centered interface between the ARToolkit and any 3D modeling software that utilizes. 3DS files such as 3DSMAX, MAYA, and CINEMA4D. In addition, animations can be directly imported into the AR interface through the attached exporters of 3D modeling software and recognized by the predefined markers without the more sophisticated exporter such as OSGExp. The standard materials and rendering effects can be securely conserved after being exported. A multimarker to enable an AR interface with the synchronous display of multiple virtual objects for assembly purpose was adopted.

## *Contents Creation of Virtual Assembly Animations*

The assembly task for the experimental evaluation should be selected to align with the practical application, and to be very representative and capable of disclosing various effects of different assembly guidance. However, the safety and manoeuvrability considerations in the experiments restrict the sizes of the assembly product. Also, the task selected should be complex enough to give rise to high demands on human cognition. Therefore, the LEGO MINDSTORMS NXT 2.0 is selected as the experimental content for the animated AR system because of each components' dimensional disparity (e.g., shape and color) (Fig. 3).

Consequently, the assembly sequence and component installation/fixation are conceived to be critical issues rather than being component-based. The LEGO model used consists of 35 spatially-functioning pieces (Fig. 4). These components are detached in advance and positioned in the workpiece stocking area. Ten participants were recruited for a pilot study to try to assemble the LEGO model. They were presented with the assembly manual and then it was removed prior to initiating the assembly process.

None of the participants were able complete the model assembly within 20 min without the guidance provided (20 min was defined



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**Fig. 3.** Snapshot of LEGO MINDSTORMS NXT 2.0 and its components

as a threshold of complexity), even though free assembly operations were allowed. 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-scaled 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; this is because of the limited size of assembly manuals. The implementation of a component/part selection process typically depends on the dimensional labels marked in the assembly manual, or the similarity of component images and physical components. It is sometimes difficult to understand the component shape in an assembly manual and the interrelations that can exist between components. It is also a challenge to visualize the spatial structure of a product when comparing different views. Fundamentally, the problems associated with informational retrieval from conventional assembly manuals can be overcome by using AR techniques. Virtual counterparts of real objects can be defined in a real-scaled size and observed (each facet of virtual objects is visible) by rotating markers, which improves an assembler's understanding of operations. In the LEGO model assembly, for example, 35 components were the same color or approximately the same size, but assemblers were able to select components correctly by comparing the real and virtual images of different parts (Fig. 5).
2. Supplemented augmentations to ease ongoing 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 hold from the right of the red piece matches the first hold from the right of black piece. The hints also provide the assemblers with the recommended assembly method. This recommendation is provided so as 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 detach the pin-hold assembly in the AR environment if the assemblers do not determine how they match together (Fig. 6). The diversified supplemented augmentations in the AR animation prototype are generated to ease the ongoing task.
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 and Majoros 1998). Each association of a virtual object with a sequential workpiece feature is a basis for linking memorial pieces in human memory. In the animated AR system, when each augmented step of assembly becomes represented on the next one (Fig. 7), this may increase performance of sequential recall.

This could be possibly 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 retrieving from physical media. Because of the difference of individual capacity in strategy of handling memorial pieces or short-term memorial store, it makes a difference among different people in terms of the effectiveness of retrieving the memory that stores previous information. The stepwise guidance enabled by the AR animation form may be facilitating the linkage of short-term memorial pieces, and thus be able to improve ergonomic performance by impacting recall capacity.

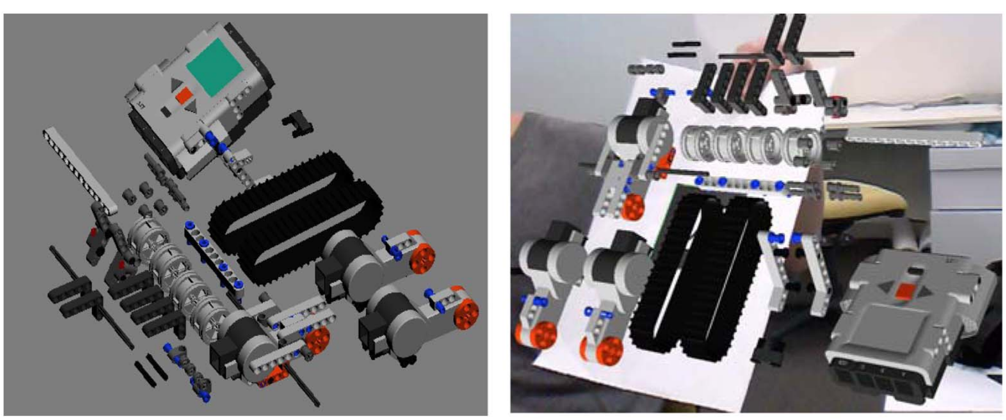

**Fig. 4.** LEGO model in 3DSMAX and the animated AR system

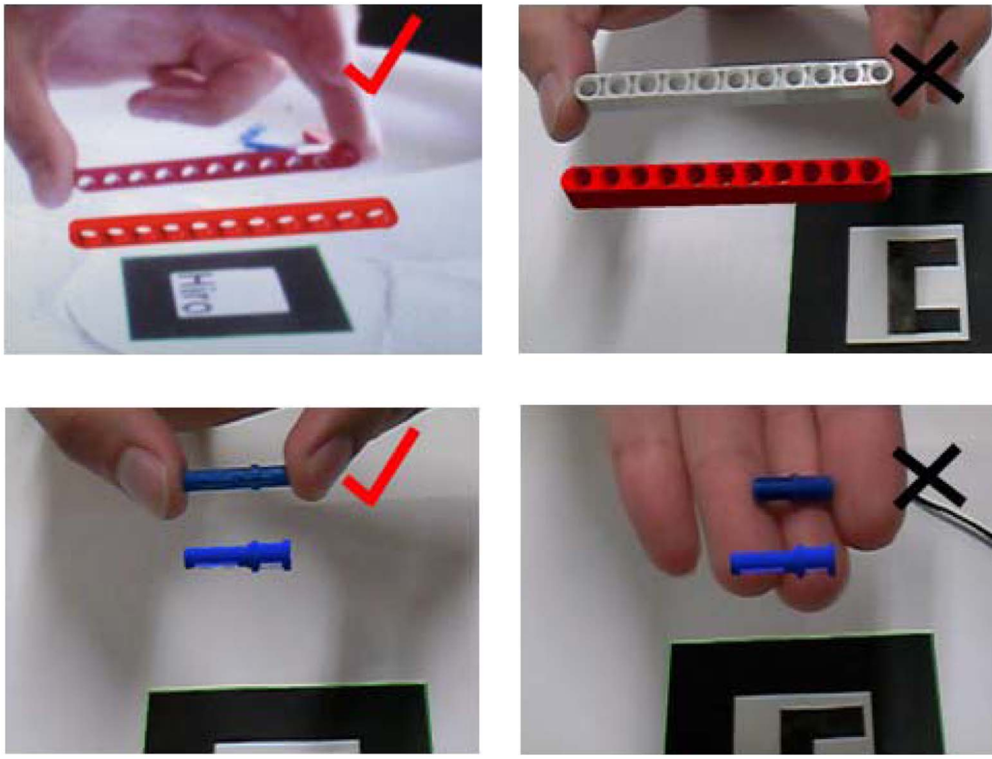

**Fig. 5.** Components matching and mismatching in terms of shape and color

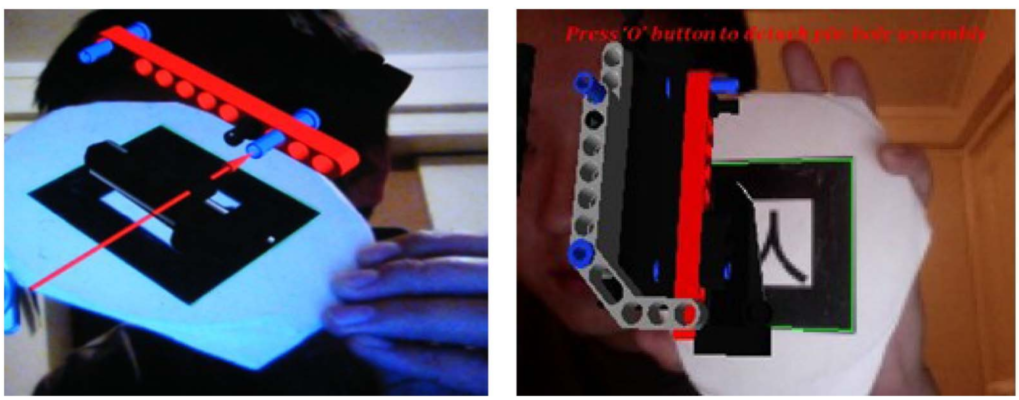

**Fig. 6.** Supplemented augmentations to ease ongoing tasks

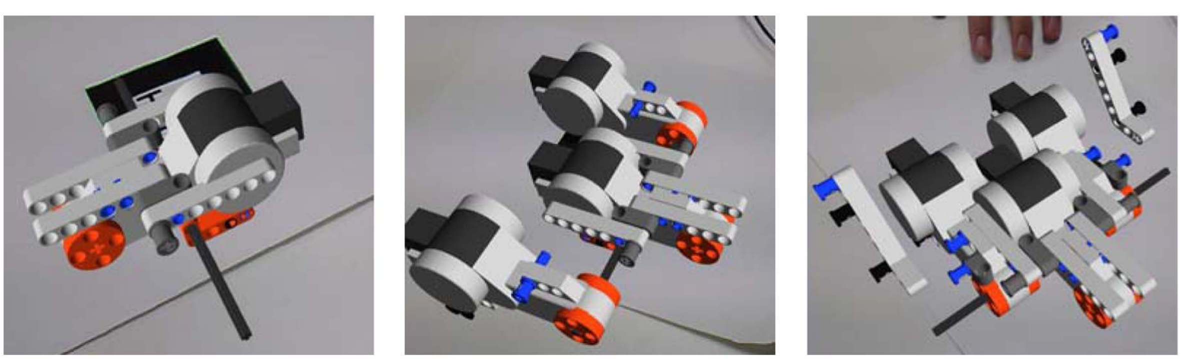

**Fig. 7.** Model is assembled step by step: completion of middle part, left and right parts, and lateral parts

## Hypothesis

The objective of this research is to examine the cognitive potentials by revealing what specific facilitations the animated AR system could lend to the assemblers, and to testify the likelihood of shortening the learning curve of novice assemblers when implementing the actual assembly or training. Based on this, the hypotheses are formulated in four types as follows:

1. When compared to a conventional paper-based manual, the animated AR system is able to lowering an assembler's cognitive workload during the LEGO model assembly task.
2. When compared to a conventional paper-based manual, the animated AR system shortens the time spent on the LEGO model selection and assembly operation.
3. When compared to a conventional paper-based manual, the animated AR system reduces the amount of assembly errors that arise.
4. Using the animated AR system as a training tool reduces the learning curve of trainees in cognition-demanded assembly. This is based on a subhypothesis that training within an AR environment facilitates longer working memory (WM) capacity compared to training with a manual.

Human memory, especially WM, normally includes certain mechanisms for forming memorial associations (chains) between representations. The formation of a memorial association (chain) is a process of linking the representations that been previously retrieved (Unsworth and Engle 2007). The lowering of cognitive workload through the enhancement of spatial cognition in the animated AR system might influence the mechanism of short-term memorial storage and retrieval. The assembler's task performance should reflect a certain level of difference after two means of assembly training, at least from the performance that is related to memorization, for instance, human behaviors corresponding to recollecting component assembly sequence and method.

## Experimentation

An experimental design pertaining to the use of the animated AR system for assembly influencing the cognitive issues is evaluated. The experimental design investigates whether users, especially novice assemblers, can be facilitated by the AR technology during assembly. Moreover, the research examines the factors hindering this facilitation. The research design assists with the identification of training effects on the posttask performance using AR and an assembly manual and the relationship between WM and learning curves. The experimental design consists of three distinct phases (Fig. 8):

1. Mental rotations;
2. Two main experiments; and
3. A usability evaluation of the animated AR system.

Mental rotations were first undertaken to examine spatial-cognitive capacity. Then, two experiments were executed to compare two scenarios: manual and AR. The objective of the first experiment is to study a person's cognitive performance when merging digital virtual information (e.g., AR animation guidance) into a real assembly workspace as compared with merging the physical information (e.g., guidance manual) into the real assembly workspace. The objective of the second experiment is to compare the learning curves of AR training with assembly manual training.

Whereas prior discussion focused on the differences between two-dimensional (2D) planar images in manual and 3D spatial images in AR, the experiments sought to isolate the animated AR system's unique advantage by using 3D forms of components

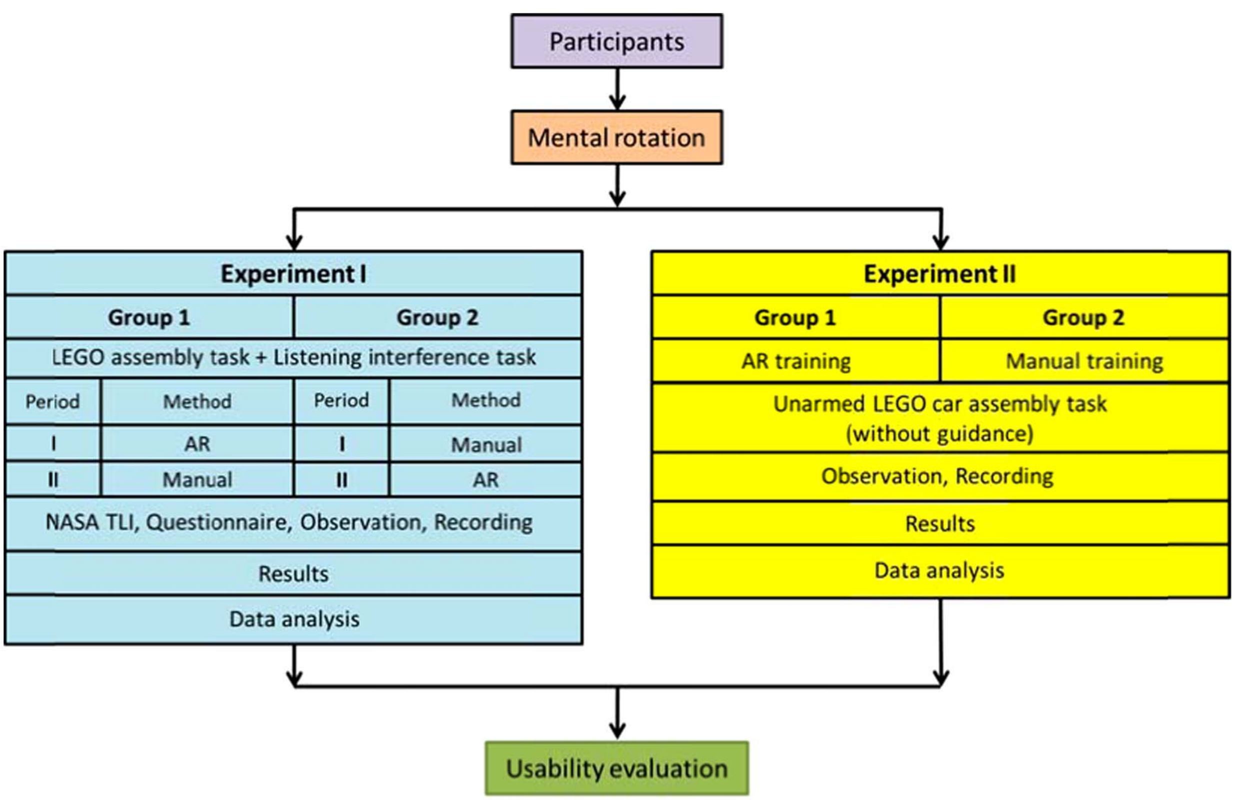


**Fig. 8.** Evaluating cognitive issues of using the animated AR system and assembly manual in product assembly tasks



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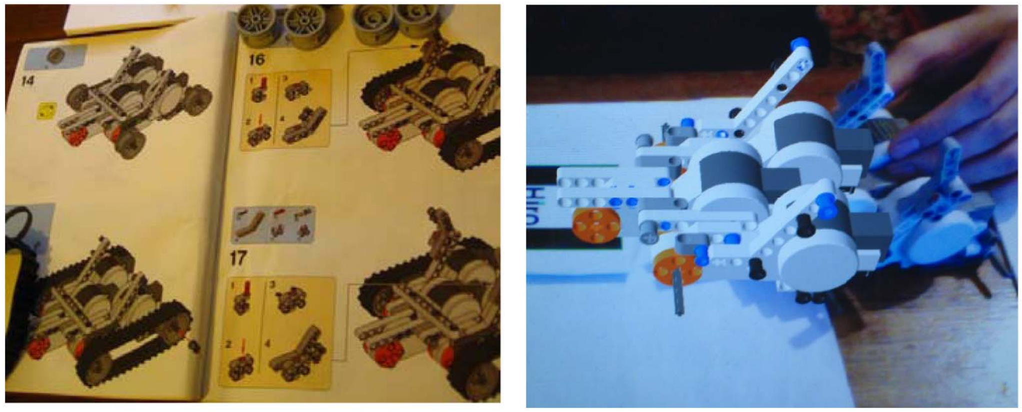

**Fig. 9.** Scenario of manual and LEGO experiments

as guidance in both cases. Therefore, scenario one was a paper-based 3D manual in which the participants could see the 3D LEGO components (Fig. 9). In this experiment, 50 graduate students from the Department of the Built Environment at University of New South Wales (UNSW) were recruited. None of them had ever used AR before. All subjects voluntarily participated in the experiments. All were informed of their rights as research participants as per the UNSW for Human Subjects Research protocol. Experiments I and II comprised of 20 and 30 participants, respectively.

### *Fore-Task-Prejudgement of Cognitive Capacity*

The fore-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 (Fig. 10). Mental rotation is regarded as a direct and convenient measurement for human capacity of spatial object cognition. Task processing refers to the procedural visuo-spatial input, mental manipulation, and back to reality (output). It is dependent on spatial capacity and cognitive workload (Zacks 2008). Therefore, the results of determining mental rotation exercise for spatial-cognitive capacity may be used to provide a baseline of each subject's capacity in this domain.

### *Experiment I—Cognitive Workload*

The objective of experiment I is to study a person's cognitive performance when merging digital virtual information (e.g., AR animation guidance) into a real assembly workspace as compared with merging the physical information (e.g., guidance manual) into the real assembly workspace. A concurrent task strategy (also known as secondary task strategy) was applied because it reflected the level of cognitive load imposed by a primary task (Dunlosky and Kane 2007). This is based on the tentative study that if the assembly task performances under the two scenarios do differentiate in participants' associated cognitive load, their mental and motor performance would be differentially influenced by the introduction of concurrent cognitive tasks (Rose et al. 2000). To those who suffer less cognitive load, they may free up their cognitive capacity to deal with interfering tasks. In the experimental design, each of the scenarios assesses different cognitive needs, and includes a secondary task to examine cognitive workloads.

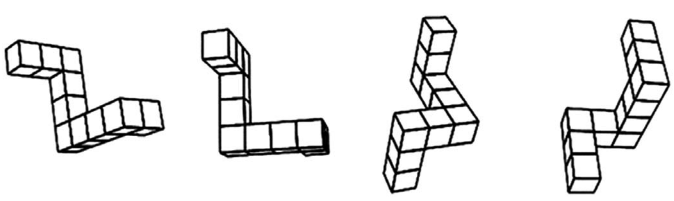

**Fig. 10.** Mental rotation [adapted from Collins and Kimura (1997)]

The physical performance of cognition-related tasks is dependent on mental process. A specific portion of mental resources are occupied by certain cognitive needs. When a secondary task is introduced, mental processes may be subject to high demands. The measurement for cognitive workload includes subjective analytical and empirical methods (usually involving a questionnaire comprising of one or multiple semantic differential scales in which the subject can indicate the experienced level of cognitive load) and a rating scale technique (which is based on the assumption that people are able to introspect on their cognitive processes and report the amount of mental effort expended) (Xie and Salvendy 2000).

Most subjective measures are multidimensional because they assess groups of associated variables such as mental effort, fatigue, and frustration, which are highly correlated. Rating scales may appear questionable, however; it has been demonstrated that people are quite capable of providing a numerical indication of their perceived mental burden (Gopher and Braune 1984). Furthermore, the physiological domain provides useful measurements for the recognition of cognitive load, which is based on the assumption that changes in cognitive functioning are reflected by physiological variables (Beatty and Lucero-Wagoner 2000).

Taking into account the complexity of measuring equipment and technical constraints, the psycho-physiological measures were not considered as evaluation tools in this research. Instead, the possible compromise is to combine the subjective analytical methods (questionnaire and interviews) and objective methods (task performance observation and videotaping) and adopting the rating scale technology based on a questionnaire [National Aeronautics and Space Administration (NASA) task load index] (Hart 2006) (Fig. 11). The subjective workload measurement techniques using rating scales are easy to use, inexpensive, reliable, able to detect small variations in workload, and provide decent convergent, construct, and discriminate validity (Gimino 2002). The objective measurement techniques are robust to conduct the susceptibility research and enable the experimental results of both subjective and objective analysis (Mulhall et al. 2004).

The two-group crossover design was used to minimize the effects from the learning curve imposed by the different experiment sequences for 20 subjects (Fig. 8). After the mental rotation quiz (18 items contained on a mental rotation test sheet), all subjects scored between 13 and 18 (evaluated as normal spatial ability). Prior to the LEGO model assembly task, the participants in the



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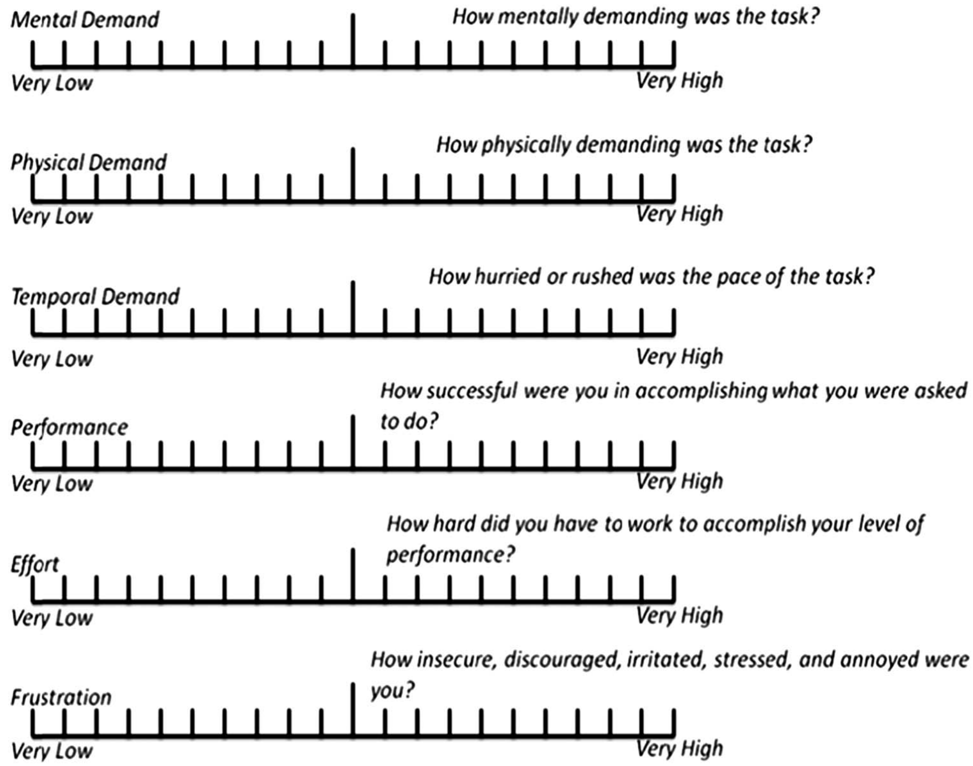


**Fig. 11.** NASA task load index based on questionnaire (Hart 2006)

two groups (10 in each) with two separate scenarios were exposed to several pictures of spatial objects and were required to remember them. In the first period (group 1 in scenario 2, group 2 in scenario 1), the subjects were simultaneously prompted to listen for the names of objects interspersed within a string of prerecorded words presented at 3-s intervals. Subjects were then asked to say yes if they heard the previously shown images of spatial objects. When they finished the first period, two groups resumed the second period, but switched over the scenarios. Therefore, errors made would be calculated based on their performance. Postexperiment questionnaires were designed to be completed based on the subjects' experience and feelings during the experiment.

## Data Analysis

Fig. 12 indicates that participants in scenario two had shorter completion times (7.37 min) compared with subjects in scenario one

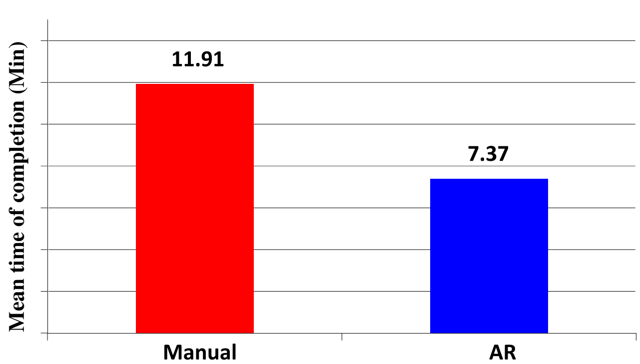


**Fig. 12.** Average time of completion in model assembly

(11.91 min). An ANOVA was conducted on the different effects of guiding methods for 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 or 0.01. When the null hypothesis is rejected, the result is statistically significant. In this experiment, the average time of completion for subjects using individual guidance is statistically significant, $F(1, 18) = 23.8$, $p < 0.001$. Thus, AR has an advantage in time of completion when compared with the assembly manual.

The AR animation provides a dynamic demonstration of consistent information context through animation segments displayed in each assembly step. The subjects were able to detect the existing dimensions from components-in-place and those registered attached to the virtually to-be-assembled components from the monitor.

Simultaneously, the animation dynamically demonstrated the assembly process by approaching the virtually to-be-assembled objects to those already assembled. This enabled subjects to mimic each assembly step and complete the real assembly operation with greater ease. By demonstrating a series of virtual animation segments registered in the real assembly space, AR is able to compensate for the mental and cognitive gaps between individual differences of information retrieval capacity and the task difficulty imposed on individuals. Consequently, AR eases information retrieval by integrating the task of searching information and the task of the actual assembly.

Offering real-time in situ assembly guidance is another characteristic feature of an animated AR system. In each step of experiment I, it was observed that the AR animation scenario dynamically and sequentially ushered the position changes of spatial components by activating each animation segment that was triggered by the subjects. When completing each animation segment, the



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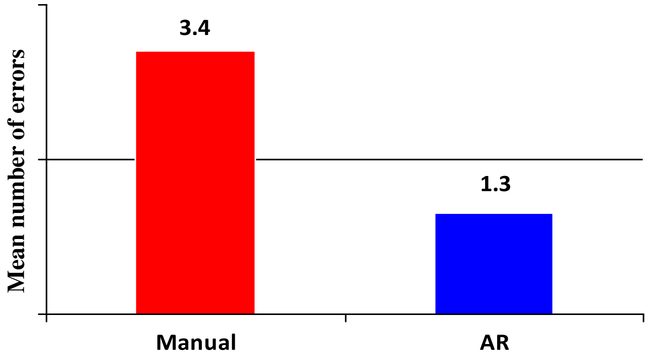


**Fig. 13.** Average number of errors in model assembly

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 subjects. During each suspended interval, the subjects were given sufficient time to pick up the components from the rest of the to-be-assembled components and position them in their final positions. The assembling operations and augmented guidance essentially proceeded together.

Fig. 13 indicates the number of errors made when undertaking the LEGO assembly task. This chart reveals that in scenario 2, subjects had a lower error rate compared with treatment 1 (3.4 versus 1.3). An ANOVA was conducted on the effect of guiding methods on error assembly. The average number of errors for AR using individual guidance is statistically significant, $F(1,18) = 6.6$, $p = 0.0193$. Therefore, AR appears to have an advantage in reducing error assembly when compared with the assembly manual.

To reduce the time it takes to complete a task, subjects may subject themselves to mental stress. Under this circumstance, it is critical that the coherence of the information context should be guaranteed to cater for the on-task assembly information retrieval. The animated AR system provides a dynamic demonstration of consistent information context through animation segments displayed within each assembly step. Subjects could detect the existing dimensions from in-place and virtually to-be-assembled components from a computer screen or projector. The animation dynamically demonstrates the assembly process by approaching the virtually to-be-assembled objects to those assembled in the correct positions. This enables participants to mimic each assembly step and lower the difficulty of the operation and task errors.

It was observed that during the experiment, some subjects using the manual as guidance often did not understand or correctly interpret the exact assembly path. With AR, perspectives can be changed easily by rotating markers. Some manual participants complained the manual was too difficult to understand, and some even reported high frustration of understanding the manual. In pursuit of speed, some subjects using the manual believed that they had understood the specific assembly steps, but had not because a number of errors were made.

Fig. 14 indicates the mean rating of the NASA task load index. The statistics show that subjects in scenario 1 had the higher mental workload than subjects in scenario 2. Rating results indicate that the subjects in scenario 2 awarded an average score 9.84, which was lower than in scenario 1 (13.64). An ANOVA was conducted on the different effects of guiding methods on cognitive load. The effect was statistically significant ($p$-value $= 0.0053$), and H1, H2, and H3 are therefore supported. The manual assembly appears to have greater mental workload for subjects, whereas AR animation has an average effect of lowering cognitive workload in the LEGO model assembly task. The animated AR system shortens the time spent on the LEGO model selection and assembly operation, and reduces the amount of assembly errors.

The higher mental demand subcategory rating involved in using the manual (16.3/20 versus 8.7/20) implies that more perceptual activities were required to complete the assembly and concurrent memorizing tasks. Trying to reason the spatial relationship of objects using the manual may have frustrated or discouraged some of the subjects, which may have induced temporal stress. These considerations can explain why the average ratings of both frustration level and temporal demand were higher using the manual (frustration score: 14.3/20 for manual and 9.0/20 for the animated AR system; temporal score: 14/20 for manual and 12/20 for the animated AR system).

Higher frustration and temporal demand levels were in accordance with the longer performance time while using the manual as the guidance tool. The $p$-value for physical demand is less than 0.001, which indicates there was a significant difference in physical demand for both scenarios. Physical demand in using the animated AR system is lower (12/20) because the subjects using the animated AR system did not consistently conduct visual transitions or movements such as page up/down. This implies that the animated AR system provided a considerably natural and comfortable way of guiding the assembly task. The close effort subcategory score for the animated AR system (8.4/20) and for the manual method (12.5/20) indicates a lower overall challenge (mentally and physically) was experienced by the subjects in accomplishing their level of performance, which was further confirmed by a significant correlation ($p = 0.52$).

### *Experiment II—Learning Curve*

The objective of experiment II was to establish learning curves for the two scenarios to study if there are significant differences in the performance between of the two groups of trainees using different

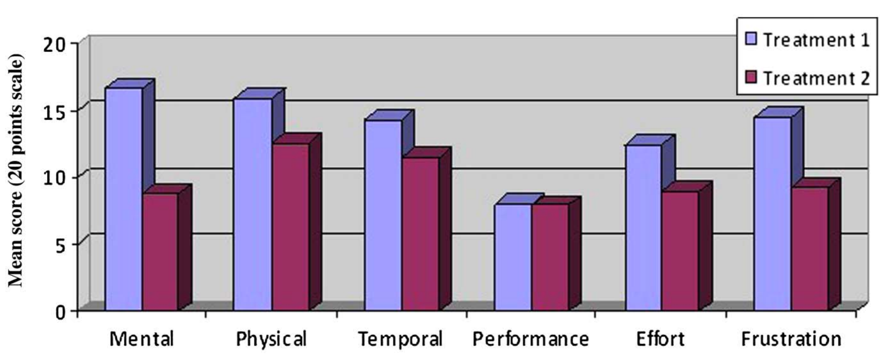


**Fig. 14.** NASA TLX scores for each item for evaluating cognitive workload in model assembly

**Table 1.** Training Methods, Number of Trials, and Mean Number of Errors in Formal Assembly

| | AR training | | | Manual training | | |
|---|---|---|---|---|---|---|
| Trial | Number of trainees | Mean errors | Number of trainees who did not err | Number of people | Mean errors | Number of trainees who did not err |
| 1 | 15 | 3.67 | 0 | 14 | 6.07 | 0 |
| 2 | 15 | 1 | 9 | 14 | 3.13 | 1 |
| 3 | 6 | 0 | 6 | 14 | 0.86 | 7 |
| 4 | — | — | — | 7 | 0 | 7 |

training schemes. According to Richardson et al. (1996), decision-making capacity reflects the time it takes the WM to glean and process the properties of the stimulus. The decision-making process applies to motor performance in which too much complexity leads to higher error rates and false moves. In addition, the span of WM of trainees depends on the characteristics of the information to be acquired.

### Experimental Procedure

Experiment II tests the effect of the animated AR system by measuring the performance of two test groups referred to as AR training and manual training denoted in Table 1. Like in experiment I, experiment II also isolated the animated AR system's unique advantage by using 3D modeling for training in both scenarios. Three metrics were used to evaluate performance:

1. Number of assembly trials until assembly was completed without an error;
2. Time consumed to complete a trial; and
3. Number of errors committed during a trial.

Prior to randomly selecting the 30 test trainees, 30 graduate students from the Department of the Built Environment at UNSW were used to pilot the experimental process. Base training, following a manual, was limited to one single LEGO model assembly cycle without a time limit. The test trainees were encouraged to remember the assembly sequence and component fixation/installation. After the base training was completed, the trainees relaxed for 5 min reading material irrelevant to the experiment (e.g., newspaper).

During this period, the assembly manual was removed, and the model pieces were laid out on a table. The two test groups of 15 students, AR training and manual training, were now starting the first trial, one group without a manual and one group without the assistance of AR. Three generic types of errors emerged:

1. Component selection error;
2. Assembly sequential error; and
3. Fixation/installation error.

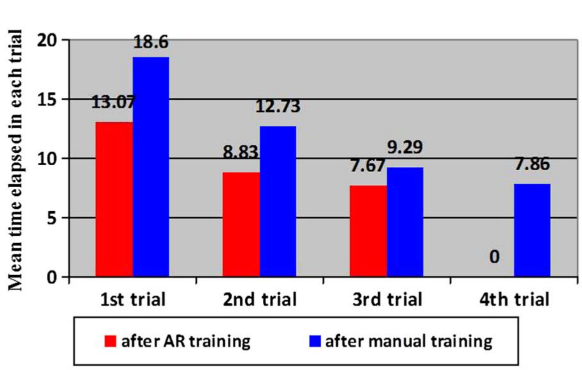


**Fig. 15.** Average time elapsed within each trial in formal assembly

Requesting help from the animated AR system or manual was also considered an error because trainees might err if no guidance was provided. The errors during unsuccessful trials were added together for each trainee and group. Subjects were videotaped during their task assignment so that potential errors could be identified. They were told how many errors were made and were allowed to check the steps in which the error had occurred. Because 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.

### Data Analysis

In Table 1, the variations in the average amount of errors during a trial are presented. For the first trial, an average of 6.07 errors were made by the manual training group compared to 3.67 of the AR training group. For the second trial, an average of 3.13 errors made by the 15 manual trainees is significantly higher than the AR trainees. The number of errors made relates to the trainees' WM effect in the formal assembly task.

**Table 2.** Statistical Results for Time Eclipsing of Each Formal Trial in Experiment II

| Trial | $F$-value | $p$-value | Significance |
|---|---|---|---|
| 1st | 21.68 | 0.001 | Significant |
| 2nd | 14.36 | 0.001 | Significant |
| 3rd | 4.29 | 0.05 | Significant |

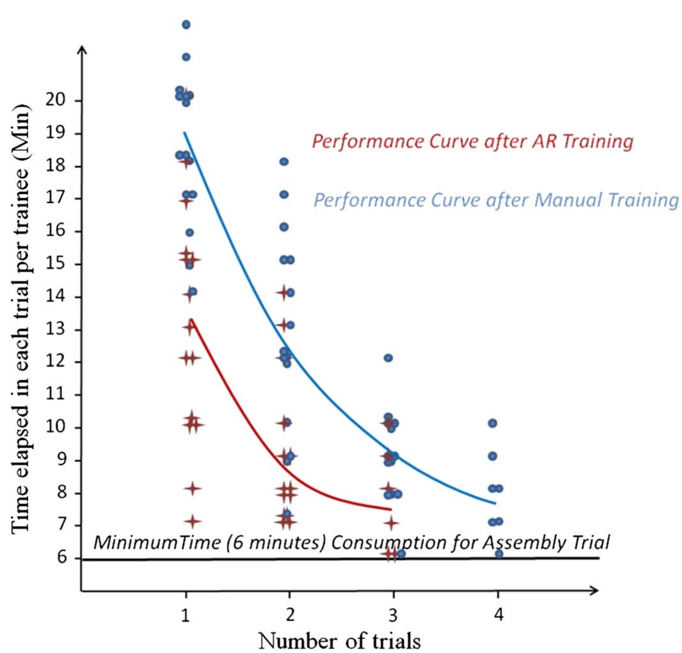


**Fig. 16.** Performance curve of conducting formal assembly



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Trainees with AR training could remember or recollect more assembly clues that were memorized in the former training task than those trained in the manual. The mean time elapsed within each trial between two trainings is depicted in Fig. 15.

A mean time of 13.07 min was needed for the trainees after AR training to complete the first trial, compared with a mean time of 18.6 min for the trainees being trained with the manual. Within the second and third trials, these numbers are 8.83 min (AR) versus 12.73 min (manual) and 7.67 min (AR) versus 9.29 min (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 ($\mathrm{SD}^{\mathrm{AR}} = 3.71$, $\mathrm{SD}^{\mathrm{Manual}} = 2.72$) is dependent on the individual training means ($p = 0.001$). Likewise, it is statistically significant for the second and third trial as well (for the second trial: $p = 0.001$, $\mathrm{SD}^{\mathrm{AR}} = 2.39$, $\mathrm{SD}^{\mathrm{Manual}} = 3.15$; for the third trial: $p = 0.05$, $\mathrm{SD}^{AR} = 1.63$, $\mathrm{SD}^{\mathrm{Manual}} = 1.59$), as depicted in Table 2.

More trials are likely to be needed until manual-based trainees complete the final trial without an error, e.g., seven manual-based trainees completed formal assembly in their third and fourth trials. The performance curve of conducting a formal assembly is presented in Fig. 16.

The data illustrate that trainees under AR training spent less time completing each formal assembly trial. Nine test participants in the AR training group were able to successfully complete the assembly after only two trials. However, only six trainees in the group without AR were successful during trial three and seven in the fourth trial. To satisfactorily complete the assembly process within the specified time period (i.e., 6 min) and without error or acquiring additional information, trainees using AR required fewer trials (2.52) than those using manual training (3.5).

To achieve a satisfactory training effect in terms of three metrics, i.e., number of assembly trials, time consumed to complete a trial, and number of errors, the AR trainees need an average of 2.5 times of trial ($\bar{t}$) and 24.83 min (Total), whereas the manual trainees need an average of 3.5 times of trial ($\bar{t}$) and nearly 42.42 min (Total). The time (Total) is calculated by

$$\mathrm{Total} = \bar{t} \times \bar{T}_{(t)} \tag{1}$$

where Total = total time of achieving satisfactory training effect; $\bar{t}$ = mean number of trials; and $\bar{T}_{(t)}$ = mean time consumption within each trial ($t = 1, 2, 3, 4$).

The use of an animated AR system as a training tool shortens the learning curve of trainees in cognition-demanded assembly, and

**Table 3.** Results and Interpretation of Usability Analysis for Animated AR System

| Issues | Mean | Summarized results |
|---|---|---|
| Navigation | | |
| Did you often feel disoriented? | 2.1 | Little disoriented<br>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? | 3.9 | Slightly apparent<br>This is one of the advantages of AR over manual. |
| Input mechanism | | |
| Did you feel annoyed or inconvenienced when operating the keyboard or marker to view different angles of the virtual image? | 1.8 | Very positive<br>Although here are still some system drawbacks, the user still expresses a positive attitude toward system control. |
| Visual output | | |
| Did visual output have adequate stability of the images as you moved with no perceivable distortions in visual images? | 3.4 | Neutral<br>It seems that the system lag is tolerable and does not affect the perception of visual image of users and therefore does not affect their performance. |
| Was the field of view (FOV) appropriate for supporting this activity? | 4.1 | Very appropriate<br>The broader the projection, the better sense the user has for the environment and communication with the AR system. |
| Did the monitor-based visual display create difficulties for observing? | 1.9 | Very easy<br>Users felt it was easy to watch the large projection or television monitor while performing the LEGO assembly task; not like the HMD, which might result in a cumbersome and uncomfortable feeling, the monitor is robust enough to support assembly. |
| Did you believe the LEGO images could be spatially matched with the physical counterparts? | 3.9 | Slightly positive<br>User felt that the virtual augmented components of the LEGO could be spatially matched with the physical components. Therefore, this characteristic facilitates the comparison and selection of assembly components, as stated in Fig. 5. |
| Was the AR display effective in conveying convincing scenes of models appearing as if in the real world? | 3.4 | Neutral<br>The virtual model looks like it is floating into the air of the real environment. Neutral rating implies that the combination of virtual model and real world reaches a level of seamlessness to some extent. |
| Immersion | | |
| With the AR system, were you isolated from and not distracted by outside activities? | 3.3 | Neutral<br>It seems that the users did not feel much distraction from outside activities by being isolated from the outside, 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? | 4.1 | Very comfortable<br>Very high score demonstrates the acceptability of animated AR system. It is not bulky, not triggering user fatigue, and not limiting user mobility. |



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training in AR facilitates longer WM capacity compared to training in a manual. Thus, the evidence provided supports H4. Sample results of questions and usability suggestions are identified in Table 3.

## Conclusions

The aim of the research was to assess the effectiveness of AR-based animation in facilitating effective and efficient learning or training of people involved in the assembly of complex systems. A set of initial experiments designed to assess the discrepancies between the traditional guidance and AR was undertaken. Results from the experiments indicate a positive effect of cognitive facilitation when using an animated AR system. When trainees relied on their memory and the manual to complete an assembly, they were prone to making errors. When AR was used, the learning curve of trainees significantly improved, and fewer errors were made. It is suggested that the use of AR technology for guiding the assembly process in the field of construction assembly will provide similar improvements. Moreover, AR can be used to guide novice assemblers when performing highly complex assembly tasks in which training time is limited and the potential for errors are either dangerous or costly. Future research will focus on testing AR with construction operations with a larger and more diverse set of trainees.

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## References

Agrawala, M., et al. (2003). "Designing effective step-by-step assembly instructions." *ACM Trans. Graph.*, 22(3), 828–837.

Azuma, R., Baillot, Y., Behringer, R., Feiner, S., Julier, S., and MacIntyre, B. (2001). "Recent advances in augmented reality." *IEEE Comput. Graph. Appl. Mag.*, 21(6), 34–47.

Beatty, J., and Lucero-Wagoner, B. (2000). "The pupillary system." *Handbook of psychophysiology*, J. T. Cacioppo, L. G. Tassinary, and G. G. Berntson, eds., Cambridge University Press, Cambridge, MA, 142–162.

Collins, D. W., and Kimura, D. (1997). "A large sex difference on a two-dimensional mental rotation task." *Behav. Neurosci.*, 111(4), 845.

Dunlosky, J., and Kane, M. J. (2007). "The contributions of strategy use to working memory span: A comparison of strategy assessment methods." *Q. J. Exp. Psychol.*, 60(9), 1227–1245.

Gimino, A. (2002). "Students' investment of mental effort." *Paper presented at the annual meeting of the American Educational Research Association*, New Orleans, LA.

Gopher, D., and Braune, R. (1984). "On the psychophysics of workload: Why bother with subjective measures?" *Hum. Factors: J. Hum. Factors Ergon. Soc.*, 26(5), 519–532.

Hart, S. G. (2006). "NASA-task load index (NASA-TLX); 20 years later." *Proc., of the Human Factors and Ergonomics Society 50th Annual Meeting*, Human Factors and Ergonomics Society, Santa Monica, CA, 904–908.

Hoffman, R. R., Crandall, B., and Shadbolt, N. (1998). "Use of the critical decision method to elicit expert knowledge: A case study in the methodology of cognitive task analysis." *Hum. Factors*, 40(2), 254–277.

Mulhall, J. P., et al. (2004). "Subjective and objective analysis of the prevalence of Peyronie's disease in a population of men presenting for prostate cancer screening." *J. Urol.*, 171(6), 2350–2353.

Neumann, U., and Majoros, A. (1998). "Cognitive, performance, and systems issues for augmented reality applications in manufacturing and maintenance." *Proc., IEEE Virtual Reality Annual Int. Symp.*, IEEE Computer Society Technical Committee on Computer Graphics and IEEE Neural Networks Council Virtual Reality Technical Committee, Atlanta, GA, 4–11.

Pastora, R., and Ferrera, L. (2009). "An improved mathematical program to solve the simple assembly line balancing problem." *Int. J. Prod. Res.*, 47(11), 2943–2959.

Richardson, J. T. E., Engle, R. W., Hasher, L., Logie, R. H., Stoltzfus, E. R., and Zacks, R. T., eds. (1996). *Working memory and human cognition*, Oxford University Press, New York.

Ritchie, J. M., Robinson, G., Day, P. N., Dewar, R. G., Sung, R. C. W., and Simmons, J. E. L. (2007). "Cable harness design, assembly and installation planning using immersive virtual reality." *Virtual Reality*, 11(4), 261–274.

Rose, F. D., Attree, E. A. A., Brooks, B. M., Parslow, D. M., Penn, P. R., and Ambihaipahan, N. (2000). "Training in virtual environments: Transfer to real world tasks and equivalence to real task training." *J. Ergon.*, 43(4), 494–511.

Salonen, T., Sääski, J., and Hakkarainen, M. (2007). "Demonstration of assembly work using augmented reality." *Proc., 6th ACM Int. Conf. on Image and Video*, Association for Computing Machinery, New York, 120–123.

Tang, A., Owen, C., Biocca, F., and Mou, W. (2003). "Comparative effectiveness of augmented reality in object assembly." *Proc., SIGCHI Conf. on Human Factors in Computing Systems Table of Contents*, Association for Computing Machinery, New York, 73–80.

Towne, D. M. (1985). "Cognitive workload in fault diagnosis." *Rep. No. ONR-107, Contract No. N00014-80-C-0493 with Engineering Psychology Group, Office of Naval Research*, Behavioral Technology Laboratories, University of Southern California, Los Angeles, CA.

Unsworth, N., and Engle, R. W. (2007). "The nature of individual differences in working memory capacity: Active maintenance in primary memory and controlled search from secondary memory." *J. Psychological Rev.*, 114(1), 104.

Veinott, E. S., and Kanki, B. G. (1995). "Identifying human factors issues in aircraft maintenance operations." *Proc. Hum. Factors Ergon. Soc. Ann. Meet.*, 39(14), 950.

Wang, X., and Dunston, P. S. (2006a). "Compatibility issues in augmented reality systems for AEC: An experimental prototype study." *Autom. Constr.*, 15(3), 314–326.

Wang, X., and Dunston, P. S. (2006b). "Mobile augmented reality for support of procedural tasks." *Proc., Joint Int. Conf. on Computing and Decision Making in Civil and Building Engineering*, Montreal, Canada, 1807–1813.

Wang, X., and Dunston, P. S. (2008). "User perspectives on mixed reality tabletop visualization for face to face collaborative design review." *Autom. Constr.*, 17(4), 399–412.

Watson, G., Curran, R., Butterfield, J., and Craig, C. (2008). "The effect of using animated work instructions over text and static graphics when performing a small scale engineering assembly." *Collaborative product and service life cycle management for a sustainable world*, R. Curran, S. Y. Chou, and A. Trappey, eds., Springer, London, UK, 541–550.

Xie, B., and Salvendy, G. (2000). "Prediction of mental workload in single and multiple task environments." *Int. J. Cognit. Ergon.*, 4(3), 213–242.

Xu, K., Chiaa, K. W., and Cheok, A. D. (2008). "Real-time camera tracking for marker-less and unprepared augmented reality environments" *Image Vis. Comput.*, 26(5), 673–689.

Yamada, A., and Takata, S. (2002). "Reliability improvement of industrial robots by optimizing operation plans based on deterioration evaluation." *CIRP Annals-Manuf. Technol.*, 51(1), 319–322.

Zacks, J. M. (2008). "Neuroimaging studies of mental rotation: A meta-analysis and review." *J. Cognit. Neurosci.*, 20(1), 1–19.

Zaeh, M. F., and Wiesbeck, M. (2008). "A model for adaptively generating assembly instructions using state-based graphs." *Manufacturing systems and technologies for the new frontier*, M. Mitsuishi, K. Ueda, and F. Kimura, eds., Springer, 195–198.

Zauner, J., Haller, M., Brandl, A., and Hartman, W. (2003). "Authoring of a mixed reality assembly instructor for hierarchical structures." *Proc., Second IEEE and ACM Int. Symp. on Mixed and Augmented Reality*, IEEE Computer Society, Washington, DC, 237–246.



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