Interactive Worker Assistance: Comparing the Effects of In-Situ Projection, Head-Mounted Displays, Tablet, and Paper Instructions

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ABSTRACT

With increasing complexity of assembly tasks and an increasing number of product variants, instruction systems providing cognitive support at the workplace are becoming more important. Different instruction systems for the workplace provide instructions on phones, tablets, and head-mounted displays (HMDs). Recently, many systems using in-situ projection for providing assembly instructions at the workplace have been proposed and became commercially available. Although comprehensive studies comparing HMD and tablet-based systems have been presented, in-situ projection has not been scientifically compared against state-of-the-art approaches yet. In this paper, we aim to close this gap by comparing HMD instructions, tablet instructions, and baseline paper instructions to in-situ projected instructions using an abstract Lego Duplo assembly task. Our results show that assembling parts is significantly faster using in-situ projection and locating positions is significantly slower using HMDs. Further, participants make less errors and have less perceived cognitive load using in-situ instructions compared to HMD instructions.

Author Keywords

Assistive systems; providing instructions; task guidance; Head-mounted Displays; In-situ projection; Augmented Reality.

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

INTRODUCTION & BACKGROUND

Providing instructions for assembly tasks is a major challenge in industrial and private settings. Especially at manual assembly workplaces, an increasing number of produced variants and an increasing turnover of staff leads to a higher demand on instruction systems. To overcome complexity and to teach assembly steps to new workers, different instruction systems for the workplace have been proposed. Traditionally, new workers are taught how to perform assembly steps from more experienced colleagues [16]. However, as companies are producing manufactured products in increasingly smaller lot sizes, a continuous assistance from a colleague is not scaleable anymore. A very common alternative without the need for human assistance or technical instruction systems is using paper-based assembly instructions. These paper instructions are usually printed on a page and placed next to the assembly workplace. However, due to the large number of manufactured products, searching for the correct printed instruction can be cumbersome. As a result, interactive instruction systems have been proposed. Most interactive instruction systems can be assigned to one of the following three groups according to the used technology: providing instructions on displays, on HMDs, or using a projector.

Displays presenting assembly instructions are either carried or worn by workers during assembly tasks. Echtler et al. [5] proposed augmenting a welding gun with a display to highlight welding spots during welding tasks. Other work suggested presenting assembly instructions using a chest worn display [18], a nearby screen [10, 14], a mobile phone [2], or a tablet computer [9]. Other research projects focus on presenting instructions on a HMD that is worn by the worker. Caudell and Miezell [4] suggest displaying drilling positions and Henderson and Feiner [12, 13] use HMDs for displaying 3D elements providing assembly task assistance. Zheng et al. [21] explore central and peripheral instruction position on a HMD. However, during long-term usage of HMDs for instructions headaches can occur [19]. Another field of research is providing in-situ instructions, i.e. projecting information directly into the workers field of view. In 2003, Sakata et al. [17] proposed using a remote controlled laser pointer as an early version of in-situ projections. Later, Bannat et al. [1] suggested using a top-mounted projector and a camera to display pictorial assembly instructions directly on the workplace and sense interaction with the camera. Korn et al. [14] use projected buttons for controlling the pictorial in-

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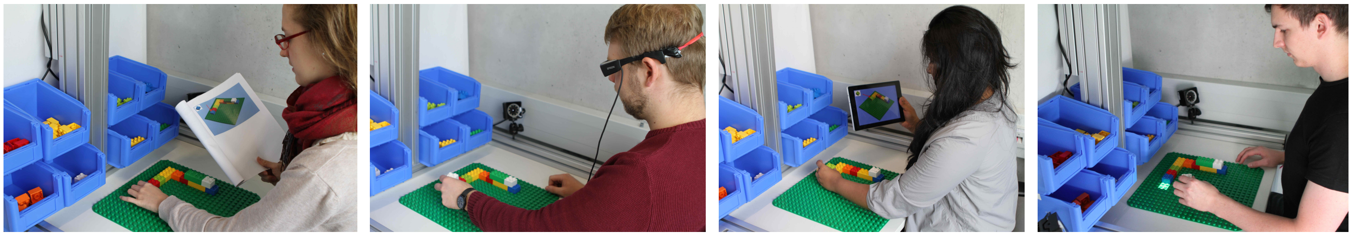
(a) (b) (c) (d)

Figure 1. We used four different instruction systems in our user study. (a) A printed paper-based instruction as a baseline, (b) a digital instruction that is presented at the center of a head-mounted display, (c) a digital instruction that is presented on a tablet, and (d) in-situ projected instructions that highlight the assembly position using a green contour that is projected directly in the workspace.

structions. Büttner et al. [3] use projected assembly instructions that are projected at a distinct instruction area. Recently, Funk et al. [7] introduced a system using a top-mounted projector and a depth camera to display contour-based assembly positions and automatically detect correct assembly. They found that cognitively impaired workers using contour-based in-situ instructions are significantly faster in assembly tasks than using pictorial instructions. Further, it has been shown that in situ-projected instructions are faster and lead to less errors than a nearby screen [15].

Comparative studies have shown that spatial HMD instructions that overlay the physical world lead to less errors than presenting pictorial instructions on HMDs, display, or paper [20]. In the domain of order picking a study showed that in-situ instructions outperform HMD, voice, and paper instructions [8]. Recently, a study comparing pictorial instructions on a tablet, paper, peripheral and central HMD [21] showed that instructions positioned at the center of a HMD are better than a peripheral position. On the other hand, in-situ instruction systems are becoming more and more popular, for example, WERKLICHT[1] from EXTEND3D and Light Guide System from OPS solutions[2] are already commercially available. Surprisingly, a comprehensive scientific comparison that also includes in-situ instructions has not been conducted yet.

With this paper we aim to close this gap by comparing four different systems for providing instructions at the assembly workplace. Through a user study, we compare paper, tablet, HMD, and in-situ projected instructions considering assembly time, number of errors, and perceived cognitive load.

EVALUATING INSTRUCTION SYSTEMS

Informed by related work, we identified four main categories of instruction systems: First, HMD-based instruction systems, where the user is viewing instructions using smart eyewear. Second, tablet-based instructions, where the user carries a tablet containing assembly information. Third, assembly instructions using in-situ projection, where the information is directly projected into the physical world. Lastly, many research projects still use paper-based instructions as a baseline to compare them against interactive instructions. To find the most suitable instruction system, we conducted a user study to evaluate the four systems at an assembly workplace. As assembly task for the study, we are using the 32 step reference task suggested in [6]. In the following, we describe the instruction systems that we used in the study in detail.

Paper instructions

As the paper baseline, we printed the reference instructions provided in [6] on an A4 sheet of paper (see Figure 1a). We printed the instructions single-sided, such that the position of the instruction was always at the same position relative to the manual. However, this requires the worker to turn pages after each working step. Finally, we put the paper sheets together in correct order using a folder. The instruction shows a picture of the brick that needs to be picked in the upper left corner of the page. Further, the instruction shows the assembly position of the brick. To better view the assembly position, it is highlighted using a red arrow.

HMD instructions

For reproducing the exact setup suggested by Zheng et al. [21], we present pictorial instructions at the center of a HMD's field of view. Accordingly, we use an Epson Moverio BT-200. The HMD displays the same images as in the paper-based instruction using a full screen application. We connected the HMD via WiFi to enable a Wizard of Oz to advance the instruction when the assembly step was performed correctly. To ensure that the Epson Moverio BT-200 does not slip on the participant's nose, we reinforced the mounting using a rubber band (see Figure 1b).

Tablet instructions

As a digital alternative to the paper instructions, we display assembly instructions on a tablet (see Figure 1c). Therefore, we use a HTC Nexus 9 to display images of the instructions on the tablet. We use the same instruction images that are printed in the paper-based instructions and displayed in the HMD. The tablet is connected to WiFi to enable controlling the shown instructions using a wireless presenter. We designed the tablet instructions exactly as it was used by Zheng et al. [21]. Other than suggested by Zheng et al. [21], we did not instruct the participants to hold the tablet at all times.

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[1] WERKLICHT - `http://www.extend3d.de/werklichtpro.php` (last access 03-31-16)

[2] OPS solutions - `http://www.ops-solutions.com` (last access 03-31-16)

In-situ instructions

We further use in-situ instructions for displaying assembly information. Therefore, we use the system of Funk et al. [7] using a top-mounted projector and a top-mounted Kinect_v2. The Kinect_v2's depth data is used to detect picks from boxes and to detect if a part was assembled correctly. The projector displays a green light to highlight boxes to pick from. Accordingly, a green light is used to highlight the assembly position by projecting the contour of the part directly at the assembly position (see Figure 1d).

Design

We designed the experiment as a repeated measures experiment with one independent variable, i.e. the system that was used to provide the assembly instructions. As dependent variables, we considered the number of errors, the perceived cognitive load using the NASA-TLX questionnaire [11], and the four different components of the Task Completion Time (TCT) according to the General Assembly Task Model (GATM) [6]: t_{locate}, t_{pick}, t_{locate_pos}, $t_{assemble_x}$. Thereby t_{locate} is the time to locate the correct picking position and placing the hand in the picking bin, t_{pick} is the time to perform the pick, t_{locate_pos} is the time that it takes the participant to understand the instruction and place the picked part at the correct assembly position, and $t_{assemble_x}$ is the time it takes the participant to perform the assembly. To prevent a learning effect, we counterbalanced the order of the conditions according to the Balanced Latin Square.

Apparatus

The workplace that was used for the study consists of two areas. First, the spare part area, which contains eight blue picking bins which store the parts that are used in the assembly. Second, the assembly area where the parts are assembled (see Figure 1), which is limited by a green Lego Duplo plate to hold the assembly in a fixed position. Previous work recognized that Lego Duplo tasks are suitable for evaluating instruction systems [1, 7, 18, 20]. Thus, we are using the Lego Duplo reference task suggested in [6], consisting of 32 steps. The task requires 8 different Lego Duplo bricks that differ in color or shape. For the assembly area, we were using a green 24×24 Lego Duplo plate. In the spare part area, we arranged the picking bins in a 2×4 grid. We chose to use the identical 32 step task for each instruction system to ensure the same complexity for every task. To prevent a systematic learning effect, we counterbalanced the order of the instruction systems across the participants.

Procedure

After explaining the course of the study and signing the consent form, we collected the demographic information. To make the participants familiar with the used instructions, we gave the participants an introduction for each type of instruction directly before using it. The participants were instructed that the first priority of the study is to not make any errors, and the second priority is to assemble fast. For making the participants familiar with each type of instruction system, we used a different task than the one used in the study. When the participant felt familiar with the instruction system, the researcher started recording the assembly using a GoPro Hero3.

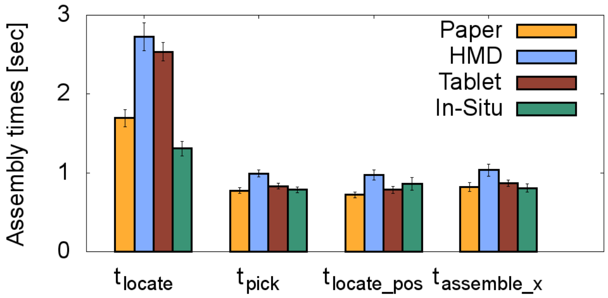

Figure 2. The average time for each type of instruction according to the GATM: t_{locate}, t_{pick}, t_{locate_pos}, $t_{assemble_x}$. Error bars depict the standard error.

We recorded the assembly to determine the exact times for t_{locate}, t_{pick}, t_{locate_pos}, $t_{assemble_x}$ proposed in the GATM [6]. In the in-situ condition and in the HMD condition the measuring of the time started with displaying the first step of the instruction. In the paper and tablet condition, the measuring started when handing the participant the instruction, as the instruction for the first step was shown right away. During the assembly, two researchers independently counted the errors that were made. We considered an error, when a wrong brick was picked and when a brick was assembled at a wrong position on the plate. In the tablet, HMD, and paper condition, we told the participants that the exact position of the first brick on the green plate is not important. They were instructed to start the assembly in the middle of the plate. However, in the in-situ projection condition, we counted a wrong absolute positioning of the first brick as an error, as the projection showed a fixed starting point and all other instructions are shown relative to the defined absolute starting position. Further, in all conditions we counted a position as wrong after the first assembly step, if the brick was at a wrong position relatively to the other placed bricks. After the task was conducted, the researchers compared the counted number of errors. In case the number of errors differed between the researchers, they watched the recorded video and reached an agreement. After each condition, we asked the participants to complete a NASA-TLX [11] questionnaire. Then we asked them for their opinion about the instruction system. We repeated the procedure for the other conditions. Overall, the study took approximately 30 minutes.

Participants

We recruited 16 participants (7 female, 9 male) via our university's mailing list. The participants were aged from 20 to 33 (M = 25.43 SD = 3.59). All participants were students with various majors or PhD students. They were not familiar with the assembled Lego Duplo task. Participants were rewarded with candies for participating in our study.

Results

We statistically compared the TCT divided into t_{locate}, t_{pick}, t_{locate_pos}, $t_{assemble_x}$, the number of errors, and the NASA-TLX score between the feedback modalities using a one-way ANOVA. Mauchlys test showed that the sphericity assumption was violated for the number of errors ($\chi^2(5) = 13.013$,

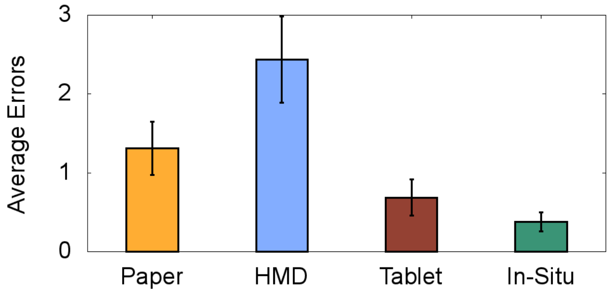

Figure 3. The average number of errors that were made during the study using the different instruction systems. Error bars depict the standard error.

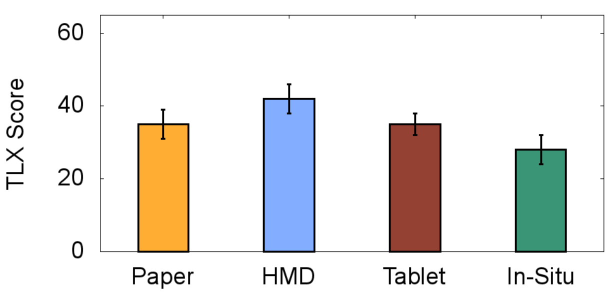

Figure 4. The average perceived cognitive load (RTLX score) that was perceived by the participants when using the different instruction systems. Error bars depict the standard error.

p = .024), and t_{locate_pos} ($\chi^2(5) = 13.765$, $p = .017$). Therefore, we used the Greenhouse-Geisser correction to adjust the degrees of freedom ($\epsilon = 0.668$ for number of errors, and $\epsilon = 0.723$ for t_{locate_pos}). We further used a Bonferroni correction for all post-hoc tests.

First, we analyzed the average time that participants needed to find the box to pick from regarding the different instructions: t_{locate}. According to Figure 2, the in-situ projection required the least time to process the instruction with an average of 1.30s (SD = 0.37s), followed by the paper instructions with an average of 1.69s (SD = 0.44s), the tablet instructions 2.53s (SD = 0.46s), and the instructions on the HMD with an average of 2.72s (SD = 0.72s). A one way ANOVA revealed a significant difference between the approaches, $F(3, 45) = 30.784$, $p < .001$. The post-hoc test revealed a significant difference (all $p < .05$) between all approaches except HMD instructions vs. tablet instructions and in-situ projection vs. paper instructions. The effect size estimate shows a large effect ($\eta^2 = 0.672$).

Considering the average time a participant needed to pick a part from a bin t_{pick}, the paper instructions required the least time 0.77s (SD = 0.13s), followed by the in-situ projected instructions 0.78s (SD = 0.14s), the tablet instructions 0.82s (SD = 0.14), and the instructions that were displayed on the HMD 0.99s (SD = 0.18). The one-way ANOVA revealed a significant difference between the types of instruction, $F(3, 45) = 13.362$, $p < .001$. The post-hoc test revealed that the feedback on the HMD leads to a significantly higher picking time than all other approaches (all $p < .05$). The effect size estimate shows a large effect ($\eta^2 = 0.471$).

The average time to locate the assembly position of a part t_{locate_pos} was the lowest using the paper instructions 0.72s (SD = 0.14s), followed by the tablet instructions 0.78s (SD = 0.17s), the in-situ projected instructions 0.85s (SD = 0.32s), and the instructions that were presented on the HMD with 0.97s (SD = 0.26s) on average. The one-way ANOVA revealed a significant difference between the types of instruction, $F(2.170, 32.551) = 7.988$, $p = .001$. The post-hoc test revealed a significant difference between HMD instructions vs. paper instructions, and HMD instructions vs. tablet instructions (all $p < .05$). The effect size estimate shows a large effect ($\eta^2 = 0.347$).

Regarding the average time to assemble a part $t_{assemble_x}$, the in-situ projected instructions resulted in the fastest assembly with an average of 0.80s (SD = .20s), followed by the paper instructions 0.81s (SD = 0.23s), the tablet instructions 0.86s (SD = 0.17s), and the instructions that were presented on the HMD 1.03s (SD = 0.31s). The one-way ANOVA revealed a significant difference between the types of instruction, $F(3, 45) = 6.182$, $p = .001$. The post-hoc test revealed a significant difference between the in-situ projected instructions and the instructions that are presented on the HMD. The effect size estimate shows a large effect ($\eta^2 = 0.292$).

Analyzing the average number of errors that were made during the assembly, the in-situ projection lead to the least errors with 0.37 (SD = 0.50) errors on average, followed by the tablet instructions with an average of 0.69 (SD = 0.94) errors, the paper-based instructions with an average of 1.31 (SD = 1.40) errors, and the instructions on the glasses with 2.44 (SD = 2.25) errors on average. The one-way ANOVA showed a significant difference between the approaches, $F(2.005, 30.070) = 7.859$, $p = .002$. The post-hoc test revealed a significant difference between the HMD instructions vs. the tablet instructions, and the HMD instructions vs. the in-situ projection. The effect size estimate shows a large effect ($\eta^2 = 0.344$). The results are also depicted in Figure 3.

Considering the perceived cognitive load using the Raw NASA-TLX (RTLX) score [11], the in-situ projection was perceived best with an average RTLX score of 28.13 (SD = 18.41), followed by the tablet with an average of 35.06 (SD = 15.48), the paper baseline with an average of 35.50 (SD = 18.19) and the HMD with an average score of 42.81 (SD = 18.28). A one-way ANOVA revealed a significant difference between the approaches, $F(3, 45) = 5.171$, $p = .004$. The post-hoc test only revealed a significant difference ($p < .05$) between the HMD and the in-situ instruction. The effect size estimate revealed a medium effect ($\eta^2 = 0.256$). A graphical representation is depicted in Figure 4.

Qualitative Results

We analyzed the statements of the participants after assembling the Lego Duplo bricks according to each of the instruction systems. For the HMD instructions, the participants mostly stated that *"the displayed instruction blocks the sight on the assembly and the boxes that contain the bricks"* (P2, P3, P4, P7, P9, P11, P12). Further, they told us that *"when I am focusing a point that is very close, the HMD shows two pictures, which makes the instruction hard to see"*. However, they liked that *"the HMD instructions enabled [them] to assemble with both hands"*. Considering the tablet instructions, participants liked that *"compared to the paper instruction, there is no chance that [I] skip a page unintentionally"* (P13). On the other hand, P4 stated that *"the tablet interferes with the assembly task as I can only use one hand"*. The paper instructions were perceived well by the participants, as they *"can put [them] away if [they] don't need them anymore"* (P14, P16). On the other hand, a participant stated that he *"needed to double check if [he] didn't skip a page"* (P13). Finally, for the in-situ instructions, the participants liked that they *"have both hands free during the assembly"* (P4, P8) and that they *"don't need to think to transfer the instruction to the work space"* (P2, P12, P14). On the other hand, they remarked that *"the projection could be brighter, as it was hard to notice on blue bricks"* (P7).

DISCUSSION AND LIMITATIONS

Interestingly, the paper-based assembly instructions performed relatively well in comparison with the interactive in-situ instructions. This might be caused by the good design of the paper-based instructions, i.e. highlighting relevant parts using a red arrow and using one page per work step. Therefore, a general validity of the results of the paper-based instructions for assembly workplaces in industrial settings might not be given as the design of paper-based instructions varies in industrial settings. Considering that in some industrial settings paper-based assembly instructions only consist of a picture that the reader has to compare to the previous image in order to learn where the next part has to be assembled, the performance of the paper-based instructions is dependent of the design of the instructions. However considering the internal validity, the results are valid as the same well-designed instruction was used for paper-based, tablet, and HMD instructions.

In general, in this study we are using implementations of instruction systems that were suggested and proven to be superior in previous research [6, 7, 21]. It has to be mentioned that other implementations or variants of the same instruction system might have yielded different results. Further, the experiment was conducted in a lab setting, using the systems in a real assembly scenario might perform differently.

Further, the results presented in this study are valid for single-user manual assembly workplaces. However, in a scenario where multiple users are assembling at the same assembly workplace, the comparison might yield different results as projection is visible to all users. On the other hand, the HMD, paper, and tablet instructions are only visible to the user who is using the instructions. Therefore, for multi-user scenarios, an instruction system that is only seen by a single user might be more suitable.

CONCLUSION

In this paper, we evaluated different instruction systems for providing assembly instructions at the workplace. We compared centrally-positioned HMD instructions, to tablet instructions, in-situ projected instructions, and paper instructions. Considering the assembly times, our results show that locating a part is significantly faster using in-situ projection and paper-based instructions, picking a part is significantly slower using central HMD instructions compared to other instructions, locating assembly positions is significantly slower using HMD instructions compared to tablet and paper instructions, and assembling is significantly faster using in-situ projection compared to HMD. Especially the time to locate a part was twice as long using HMD instructions and tablet instructions compared to in-situ projected instructions. Further, participants made significantly fewer errors using the tablet and in-situ instructions compared to the HMD instructions. Moreover, the perceived cognitive load using the NASA-TLX [11] questionnaire is significantly lower for the in-situ instructions compared to the HMD instructions. Participants liked that they have hands free using in-situ instructions. In contrary to Zheng et al. [21], our participants found that the central HMD instructions blocked their field of view. Similarly to Zheng et al. [21] our participants stated that holding tablet or paper instructions during assembly tasks interferes with assembling using both hands.

Although, the paper baseline was not significantly worse than in-situ projection, we believe that the hands-free character of in-situ projection will have great potential for instruction systems at the workplace, as HMD instructions have problems being accepted by workers and tablet instructions interfere with a two-hand assembly. In future work, we want to further investigate the effects of in-situ projection by conducting studies with a broader set of participants, investigate real assembly workplaces in the industry, and explore long-term learning possibilities using the different instruction systems.

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