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Error Communication in Manual Assembly Through a Projection-Based Assistance System

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ABSTRACT

Humans remain integral in manual assembly within manufacturing, extensive research has focused on optimizing worker support through assistance systems to address challenges such as high-quality standards and product variability. Although projection-based instruction appears promising, it currently lacks in-process quality control. This study explores real-time error communication's impact on worker performance and self-assessment, evaluating usability, task load, and subjective performance. An on-site manual assembly station was set up and 12 participants have taken part in the study. Their task was to complete an assembly task based on instructions projected onto the work surface. In the control condition, participants independently navigated through the description of instructed assembly steps using displayed arrows. The experimental condition used a Wizard-of-Oz experimental design in which participants were informed that the assistance system automatically recognizes their process and detects errors. In the case of an error, a correction prompt emerged instead of the next instruction step. No mean differences could be found between the error communication group and control group except for a significant difference in the usability of the systems. Limitations are discussed and implications for further research are derived.

Keywords: Error communication, Assistance system, Manual assembly

INTRODUCTION

The significance of manual assembly persists in various industries, particularly in tasks such as directed automotive part assembly, where automation faces economic and technological (e.g. complexity) limitations. Human workers, therefore, continue to be an essential part of manufacturing, especially for Small and Medium-sized Enterprises (SMEs) (Casalino et al., 2021). In the future, both technological and market advancements driven by digitalization and connected production systems pose challenges to manual assembly workers (Spena et al., 2016). The dynamic nature of assembly tasks, influenced by higher product variability and mass customization, necessitates a high degree of flexibility from workers, even as the expectation for high-quality outputs persists (Cohen et al., 2017; Johansson et al., 2016). In addition, there is the challenge of a skilled labor shortage in Germany (Anding, 2018), requiring innovative solutions that automation alone cannot adequately address (Pfeiffer, 2016). These circumstances demand a broader skill set from individual assembly workers, prompting the need to acquire new competencies (Bauernhansl, 2017). Therefore, it has to be investigated how the assembly workers can be supported target-group specifically.

In this context, Augmented Reality (AR) emerged as a promising medium for assistance systems supporting the assembly worker in addressing the multifaceted challenges. AR-supported systems not only hold the potential to reduce training costs significantly (Wang et al., 2016) but also accelerates the training process and contributes to shorter assembly times in the subsequent assembly tasks (Pathomaree and Charoenseang, 2005). Beyond the application context for training workers, the facilitation of in-process quality assurance by AR technology has been a recent research topic. This can be realized by real-time feedback for error prevention or feedback on the correct execution of assembly steps and potentially results in a reduction of the production of defective parts and thus the need for rework. However, amidst the optimism surrounding AR, counterarguments question its effectiveness in reducing human errors. Suggestions are that current AR technology may not be advanced enough to sufficiently address human-caused mistakes, potentially rendering the use of AR devices ineffective (Qeshmy et al., 2019). Especially, realizing the real-time objection recognition of the assembly parts with obstacles like occlusion of the parts by worker's hand occurring in manual assembly is a yet unsolved technological challenge (Thamm et al., 2021). Associated with its technical feasibility raises the question of whether this kind of in-process error communication is beneficial for the worker.

Thus, this study aims to contribute to the ongoing discourse by exploring how AR-based assistance systems can best support manual assembly workers. Specifically, we investigate whether real-time error communication can offer additional support to workers in the assembly process by imitating the functionality of such a system.

The subsequent section delineates the current state of research on AR-based assistance systems in manual assembly, resulting in the formulation of the research question for this paper. This is succeeded by a description of the methodology employed and a presentation of the study's findings. The discussion section comprehensively synthesizes the results and provides an outlook on future implications.

STATE OF THE ART: AR-BASED ERROR COMMUNICATION IN MANUAL ASSEMBLY

AR is a technology that enables the precise overlay of computer-generated virtual imagery onto physical objects in real time. In contrast to virtual reality (VR), where users are fully immersed in a virtual environment, AR allows users to seamlessly interact with virtual images using real-world objects. An accepted definition of AR as a technology is that it (1) merges real and virtual imagery, (2) facilitates real-time interaction, and (3) aligns virtual imagery with the actual environment (Azuma, 1997).

Leveraging Augmented Reality (AR) as the instructional medium in manual assembly offers several well-established advantages. Primarily, the expansion of the user's visual experience from the physical world to the informational space facilitates communication with tangible objects. This augmentation contributes to an enhanced comprehension of target objects, thereby deepening the usability and reliability of assembly operations (Henderson and Feiner, 2011; Syberfeldt et al., 2015; Westerfield et al., 2015). The application of AR instructions adheres to user cognition principles, thereby improving communication efficiency between assembly systems and users (Wang et al., 2021). Compared to conventional instructions, AR provides a more natural, intuitive interactivity and three-dimensional performance (Büttner et al., 2017; Yuan et al., 2008). Numerous studies indicate that incorporating AR into on-the-job training scenarios can significantly enhance both quality and efficiency (Dey et al., 2018).

Apart from using AR for the mere instruction of assembly tasks, researchers investigated the use of AR for error prevention to improve the performance of manual assembly in terms of effectivity and quality assurance: A primary focus application of error prevention has been the communication of picking errors. For instance, a system sets human movements in the workstation environment, utilizing an app that marks the location of the component for the next step and provides immediate feedback on whether the correct box was selected (Faccio et al., 2019). Furthermore, various feedback modalities, including haptic and auditory, have been compared, with the feedback related to grasping areas, specifically whether the correct component box was accessed. Communication occurred on a visual level through the illumination of red light, haptic feedback through vibration in a glove, and auditory feedback through a signaling tone. It was found that auditory feedback was perceived as distracting, and the combination of haptic and visual feedback proved to be effective (Funk et al., 2016). In a different variation, not only were the corresponding picking boxes illuminated in red, but the entire work surface was colored, resulting in a faster assembly time compared to auditory and haptic conditions (Kosch et al., 2016). Another study investigated the effect of real-time feedback on the applied forces of a screw connection reporting that it supported the superiority in terms of time on task, number of errors, and subjective perception regarding the usability of the training system of virtual training compared to a video-based training (Loch et al., 2019).

In addition to the known disadvantages of AR in assembly, accuracy level, or safety aspects, it is reported that the systems do not provide adequate help for experts for whom the detailed description is not necessary and even slows them down in assembly times (Funk et al., 2017; Mark et al., 2020). This may lead to less frequent use of such assistance systems by experts in manual assembly. Yet human errors occur, so how can the performance still be supported? One solution might be real-time error feedback, although its effects on the worker are still unclear; thus this leads to the research question:

What are the effects of immediate/real-time error communication within manual assembly on the user in terms of perceived task load, system usability, subjective performance, as well as performance criteria such as assembly time and committed errors?

METHODOLOGY

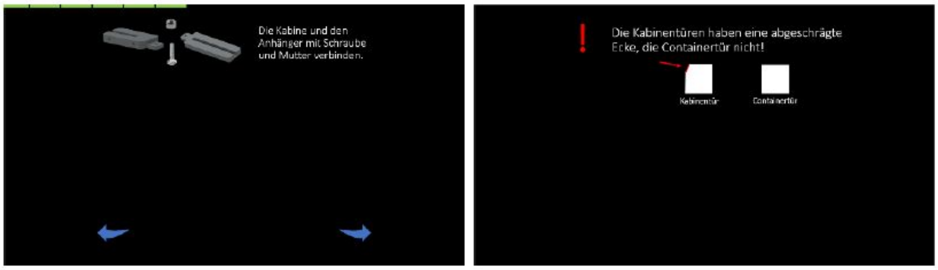
The sample consisted of 12 participants (M_{age}: 28,33 years SD: 5,02; 50% female) who were students and employees of the university and participated voluntarily without any incentives. An on-site manual assembly station was set up. The main element of the study was the completion of an assembly task based on instructions projected onto the work surface. The task was to assemble a 3D-printed truck (Fig. 1). The 27 components of the truck had to be assembled in 14 steps including performing plug connections, and screwing operations by hand, and with a manual screwdriver. The study setup (Fig. 1) was located within a shopfloor of the university to imitate a realistic shopfloor environment where assembly tasks are performed in practice. During the experiment, the participant stood in front of a table and all the necessary parts for the assembly were in boxes within reach range. A camera recorded the assembly area which captured the hands of the participants. Assembly steps were displayed on the work surface using a projector-based system.

Figure 1: Assembly task: 3D-printed truck model (left), experimental setup from the participant's perspective (right).

The participants were randomly assigned to a control group (n = 6) and an experimental group (n = 6). In the control condition, participants independently navigated through the description of instructed assembly steps using displayed arrows. The experimental condition used a Wizard-of-Oz experimental design in which participants were informed that the assistance system automatically recognized their process and detected errors. In the case of an error, a correction prompt (Fig. 2) emerged instead of the next instruction step.

There were two researchers, one of whom was present, welcomed the participants, explained the setup and assembly task, handed them the declaration of consent including consent recording a video of their hands while assembling, and guided the participants in general through the experiment.

The other one was hidden to imitate the automatic functioning especially the error communication of the assistance system. The latter stood behind a wall facing the participant and observing the participant's hands via the camera. His task was to display the instruction to the participant at the right time imitating an automatic system. The instruction was facilitated by a PowerPoint presentation and consisted of single written phrases and CAD pictures of the components necessary for the corresponding assembly step (Fig. 2). Additionally, in the experimental group, if the participant made an error, they displayed an error message communicating that the participant made an error and how to correct the error. Meanwhile, the investigator recorded the assembly time and documented which errors were made.



Die Kabine und den Anhänger mit Schraube und Mutter verbinden.

Die Kabinentüren haben eine abgeschrägte Ecke, die Containertür nicht!

Figure 2: Instruction with arrows in the control condition (left), error communication in the experimental condition with a hint of how to correct it.

After finishing truck assembly, the participants completed questionnaires on their perceived workload, system usability, and control beliefs in dealing with technology. The NASA TLX Questionnaire (Hart and Staveland, 1988) operationalized perceived workload with six items reaching on a 100-step scale from low to high exemplary for the item mental effort, "how much mental effort was required to absorb and process information (e.g. thinking, deciding, calculating, remembering, looking, searching...)? Was the task easy or demanding, simple or complex, did it require high speed or is it error-tolerant?"

The System Usability Scale (SUS) (Brooke, 1996) measured usability using ten items on the 5-step scale "do not agree at all" to "fully agree". One of the used items was "I thought the various functions in this system were well integrated".

Moreover, we measured subjective performance and assessed the demographic information of the participants. The scale of subjective performance was created by a colleague and used in a former experiment. It consisted of four questions like "How satisfied were you with the quality of your work?" which were assessed by the participants on a 5-step scale reaching from "not at all" to "extraordinary".

Finally, the hidden investigator revealed themself and enlightened the participants about the non-automatic functionality of the assistance system and the purpose of the study.

RESULTS

The data was analyzed using SPSS software, determining the descriptive statistics (Tab. 1). Following, a Mann-Whitney-U-Test was calculated to determine if there were differences between the control group and the experimental group. The distributions differed between both groups, Kolmogorov-Smirnov $p < .05$. There could not be detected any significant differences in the objective performance measures assembly time and number of errors. For the worker-related measures task load, which was in the lower range of the scale (for both groups around 30 on a scale from 0 to 100) and subjective performance did also not differ significantly between the control group and the experimental group. There was a statistically significant difference in usability between both groups, $U = 5.00$, $Z = -2.093$, $p < .05$. The mean value of the control group was 88% over 80%, which indicates good to excellent usability. At the same time, the experimental group reported an average usability of 76% which does not have a borderline of 80% indicating good usability.

Table 1. Descriptive statistics.

		N	Min	Max	Mean	SD
Assembly time (in min)	Control	5	6.11	14.51	8.50	3.60
	Experimental	6	6.13	17.33	8.88	4.18
Number of errors	Control	6	0	7	2.83	2.48
	Experimental	6	1	7	3.83	2.04
Task Load (Scale 1-100)	Control	5	15.00	41.67	30.67	11.01
	Experimental	5	18.33	45.00	28.50	10.31
Usability (max. 100)	Control	6	70.00	97.50	88.13	10.05
	Experimental	6	66.25	85.00	76.67	7.40
Subjective Performance (Scale 1-5)	Control	6	2.25	4.75	3.95	0.96
	Experimental	6	2.00	4.75	3.54	0.89

DISCUSSION

The present paper aimed to investigate if real-time error communication regarding the correct execution of manual assembly steps is an additional support for workers. We compared an experimental group, which was assembled with the support of real-time error communication, with a control, which received the same projection-based instruction without error communication. We found no statistically significant differences regarding assembly performance (assembly times and errors) perceived task load, and subjective performance between the group with and without error communication. At the same time, a statistically significant difference was discovered regarding the system's usability. The control group showed a higher mean value in usability.

Concerning the similarity of the assembly performance of the groups one can say that error could be easily detected by the worker himself at the latest in one of the next assembly steps. Thus, the control group would also detect and correct their errors since all steps were reversible and easily corrected. Moreover, as expected both groups made a similar number of errors because the error communication occurred reactively and not proactively. Therefore, the group needed the same time to correct those errors. However, in other contexts, there could occur errors that cannot be detected during the sequent assembly and would produce defective parts or rework. A follow-up experiment could consider those aspects by reducing the detectability of errors and increasing the complexity of the necessary corrective actions.

The groups did not differ in their rather low level of perceived task load. This suggests the task complexity is not high enough that the support through the error communication would reduce especially the mental load. Error communication could relieve the worker from worrying about making an error and being solely responsible for possibly causing defective parts or rework. The usability of the systems differed significantly. The control condition system having higher usability could indicate that the participants are not used to the automatic correction of their actions and could be intimidated by the system's surveillance with error communication. Furthermore, this result indicates that the design of the error communication was not optimal and must be examined what design features contribute to good error communication. Concerning the subjective performance, no differences were found. This indicates that the fact that the errors were pointed out to the experimental while the control group might unknowingly commit errors had no impact on the subjective performance. Future studies could investigate the difference between error communication during the assembly and error communication at the end of the assembly since the possibility of correction could affect subjective performance. All those interpretations must be validated by studies confirming those small mean differences and augmented with statistical analyses with bigger samples. The external validity of the study could be raised by using assembly workers as participants and a more complex assembly task. Although the wizard-of-Oz study design seems to be a valid approach to examine the effects of technologies before they are reliably functioning, we cannot be sure if every participant believed the manipulation. We included an estimation of the experimenters in the protocol, and they reported doubt about that for a least one participant of the experimental group.

OUTLOOK

Although the approach of the imitated system seems to be suitable for further examination of reported weaknesses of previous systems through real-time feedback on committed errors, the setup has to be examined further concerning its robustness. For instance, the slowing down of assembly time for experts, caused by the display of detailed explanations or even distractions (Funk et al., 2017; Mark et al., 2020), could be mitigated by using only error communication without instructions. The extent to which such an approach can adequately support users with different levels of experience remains to be investigated. Especially a system adapting to the experience level of workers and how this adaption is implemented and perceived by the workers can be a future research direction. Despite various advantages of the Wizard of

Oz approach the impact of e.g. the response time of a real system cannot be evaluated with this method. Therefore, studies with a fully functioning system should be conducted in the future. Also, ethical issues concerning for example workers' privacy (Funk et al., 2016) of systems monitoring workers closely have to be considered in future studies.

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