eleed
e-learning
& education

Issue 16
2025

Support for a complex assembly task through augmented reality instructions with see-through data glasses

Comparison with smartphone and paper instructions

David Mack
D.Mack@uni-kassel.de

Ludger Schmidt
L.Schmidt@uni-kassel.de

Human-Machine Systems Engineering
University of Kassel
Mönchebergstraße 7
D-34125 Kassel

Abstract

The study presented here deals with the assembly of an emergency door release handle for unlocking the doors of railway vehicles at a realistic workstation with different instructions. For this purpose, a new AR instruction with see-through data glasses was developed and compared with smartphone-based AR instructions and paper instructions. The paper instructions represent the status quo of the assembly process. The implementation with see-through data glasses is technically more complex but has the advantage over the previously analysed smartphone that the hands are free for assembly. The hypotheses investigated are that the type of instruction has an influence on the assembly time, the number of errors, the usability and the strain on the assembler. Each type of instruction was studied with eight subjects and five assembly runs in a between-subjects design. There was no significant difference in total assembly time between the see-through data glasses and the smartphone. A comparable number of errors with lower strain makes the see-through glasses still interesting for knowledge transfer.

Keywords: e-learning; Augmented Reality; Head-Mounted Display; See-Through Data Glasses; Training; Manufacturing; Digitalisation.

1. Introduction

Despite an increase in the digitalisation in production companies and in the use of robots, especially collaborative robots in automated production (Janson 2023), there are still assembly jobs that are purely manual. The reasons for this are often an excessive number of variants combined with low production volumes which leads to increasing demands being placed on employees (Franke 1998). Moreover, assembly workplaces generally have a high turnover rate, which means that new employees have to be trained frequently (Hammermann et al. 2019).

One approach to improve the comprehensibility of work and assembly instructions can be the use of innovative methods such as augmented reality (AR) and virtual reality (VR) (Schmidt et al. 2005). While not being widely used in industry yet, it is expected that their use will increase in the coming years (Klöß and Streim 2022).

The term augmented reality describes the supplementation or extension of reality with virtual content (Dörner et al. 2013), which is registered in real time, interactively and spatially correct (Azuma 1997). In addition to displaying virtual content on a transparent screen of see-through data glasses (optical see-through) (Tönnis 2010), screens can also be used to augment the camera video with content (video see-through) (Haoming et al. 2021). By combining this with the optical tracking method of marker tracking, simple AR applications can be created that can be used, for example, with a smartphone or tablet. In addition to black and white patterns, other images can be used as markers. These are recognised by the device's camera and used to display virtual content in the correct position in relation to the respective marker (Tönnis 2010). Marker-based AR is a low-cost option for deploying AR, as it only requires a camera to capture the markers and usually free programming software (Tönnis 2010). Additionally, the markers are simple to use and easy to learn, even for non-experts as well as being quick to create, print out and place anywhere (Dörner et al. 2013).

AR for assembly has been the subject of research for some time (Caudell and Mizell 1992). However, publications often have severe limitations when simulating assembly tasks with toy building blocks or using monitor-based AR with a fixed perspective that does not follow head movements (Yang et al. 2019).

Studies show contradictory results when it comes to supporting AR instructions with see-through data glasses. One publication investigating the use of HoloLens 1 to support the operation of a machine found that subjects working with visual support using HoloLens 1 were slower and made more errors than comparison groups supported by paper instructions, visual instructions on a screen, or verbal instructions (He et al. 2019). A study was also conducted with a HoloLens 1 using an assembly support application, which showed no significant difference in assembly speed compared to paper instructions (Deshpande and Kim 2018). Both studies criticise the usability of the device, in particular the small field of view of the HoloLens 1 (Deshpande and Kim 2018). However, other studies using the HoloLens 1 show an improvement in error rate and assembly speed (Lampen et al. 2019). In a study in which the HoloLens 2 was used to support visual quality control, it was shown that the improved field of vision in combination with the significantly more accurate tracking compared to the HoloLens 1 could lead to an acceleration of quality control through the AR application (Seeliger et al. 2023). Otherwise, the number of publications with HoloLens 2 that explicitly investigate assembly with real components is very limited or have a different focus. However, a publication on assembling toy bricks concludes that although the end result is better with the HoloLens 2 than with paper instructions, using the device reduces the learning of individual steps.(Generosi et al. 2022).

Other forms of AR display show that monitor-based AR instructions can save time, especially during the initial assembly steps (Hořejší 2015). A literature review concludes that improved visualisation in three-dimensional space could enable better interaction and differentiation between real and virtual environments (Wang et al. 2016). Another literature review shows that the cognitive load of using see-through data glasses remains the same or is even reduced when compared to other forms of AR, such as a smartphone-based solution, while performance increases (Buchner et al. 2022).

These partly contradictory results, combined with the technical limitations of the glasses used, suggest that realistic training in a complex assembly scenario using state-of-the-art glasses should be examined. The low-cost model used in this study, NREAL Light, weighs 106 g and has a field of view of 52°. A search using the search terms 'NREAL Light', 'assembly training' and 'Montagetraining' in Google Scholar and Semantic Scholar revealed no comparable studies to date.

As there are contradictory statements in the previous studies, the following undirected hypotheses were used below: The type of instruction influences the assembly time (H1), the number of assembly errors (H2), the usability (H3) and the strain on the participants (H4). The focus here is on the influence of the type of presentation of the AR instructions.

In a previous study, an assembly workstation was analysed using smartphone-based AR instructions (Funk and Schmidt 2020). The AR group initially assembled more slowly than the paper group but was significantly faster by the fifth round. Instead of displaying the AR instructions on a smartphone, this study uses see-through data glasses. Despite allowing more precise tracking with depth sensors, the use of high-end see-through glasses was deliberately avoided in order to enable the introduction of low-cost AR see-through data glasses. Therefore, a simple camera-based tracking system was used. To ensure comparability with the data from the previous study, the scenario was left unchanged. The same emergency handle for unlocking the doors of rail vehicles, the same tool and the same mounting blocks were used.

Compared to other studies, this one is distinguished by its real-world application, as it was carried out in a true-to-life assembly environment using original parts. The low-cost implementation of AR see-through data glasses is ideal for teaching and training novice assembly workers. In light of recent government initiatives to recruit skilled foreign workers despite language barriers, the need for applications that reduce or even eliminate language barriers is more relevant than ever (Creutzburg 2024).

2. Methods

2.1 Assembly task

This study deals with the assembly of an emergency door release handle for the manual unlocking of railway doors. The handle is available in up to 30 different variants and is currently assembled manually at a workstation as shown in Figure 1. For the present study, an assembly table of 1800 mm x 750 mm is used in the laboratory, which corresponds to the original model.

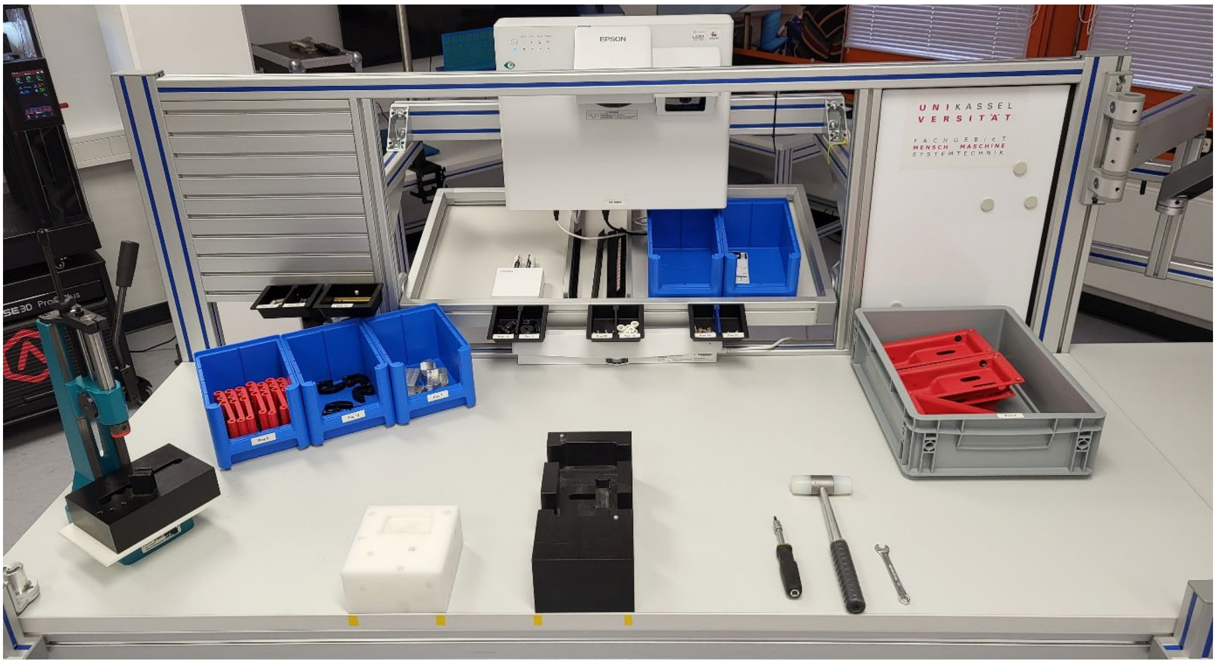

Figure 1: Assembly workstation with parts storage, assembly fixtures and a toggle press

The handle consists of 15 different components and a total of 16 individual parts that have to be put together during assembly. The following steps are required for assembly: 'positioning', 'screwing', 'inserting', 'hanging' and 'pressing'. Figure 2 on the left shows the complete model of the handle.

Figure 2: 3D model of the emergency handle to be assembled (left); tools required for assembly (middle): Hexagon socket screwdriver SW4 (1), plastic soft-face mallet (2), combination spanner SW 8 (3), assembled emergency handle (right)

The handle is assembled step by step. Assembly is carried out using assembly jigs, a toggle press and hand-operated mechanical tools, as shown in Figure 2. When all assembly operations for one emergency door release handle have been completed the next handle is assembled (Lotter and Wiendahl 2012). In practice, assembly is carried out independently after the first assembly has been carried out with the aid of paper instructions.

2.2 AR installation instructions via smartphone

In the previous study, marker-based AR assembly instructions for the emergency door release handle were used as a video see-through smartphone application. This was based on existing paper instructions that were transferred to the AR application. The assembly process was divided into seven sub-steps, each of which was labelled with a marker. The seven sub-steps consist of a total of 21 steps. Due to the technology used with the AR marker, it was necessary to divide the steps into sub-steps. Otherwise, there would be insufficient space for the markers on the table. These markers are recognised by the application and used to display the appropriate information in the correct location. At each of the seven sub-steps, the operator is presented with 3D models of the required components and a text box with the corresponding part numbers from the parts store. If necessary, further information is provided about the step to be performed. Some of the sub-steps consist of several assembly steps that build on each other. Two buttons have been integrated into the application to toggle between the displayed information. Figure 3 shows the display on the smartphone. The AR application was created using the 3D development environment Unity (version 2019.1.12f1) and the Vuforia marker-based AR-kit. In Unity, the 3D models of the assembly were linked to the markers of the corresponding sub-steps and partially supplemented with text for the part number and other notes.

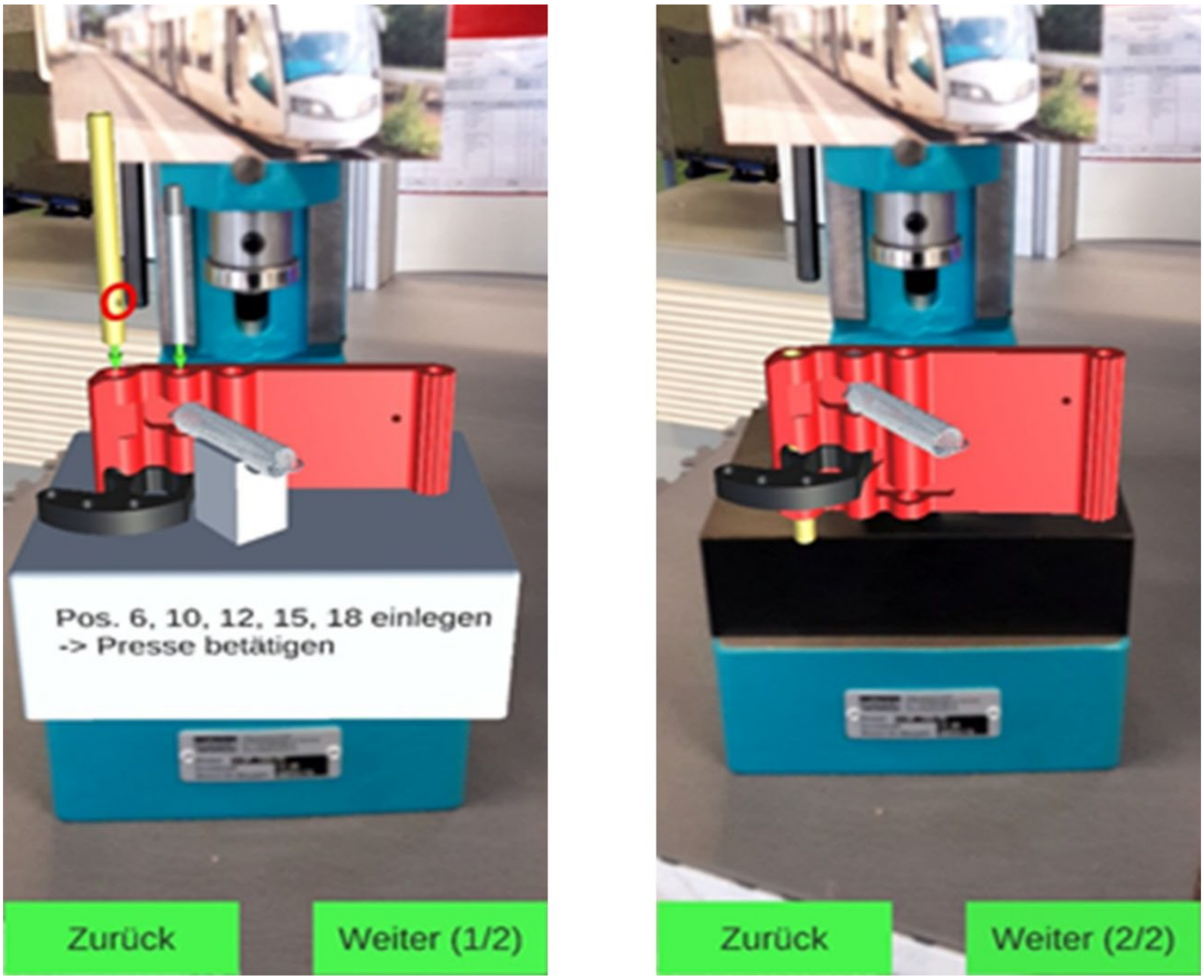

Figure 3: Smartphone AR instructions for an assembly step with indication of the part item numbers and the work request 'Operate press', 'Back' and 'Next' buttons for independently scrolling through information (left) and display of correctly assembled parts (right)

2.3 AR assembly instructions using see-through data glasses

The content of the assembly instructions was designed to work with the see-through data glasses. The assembly process was divided into 21 steps, as in the original paper instructions. Unlike the smartphone, however, the transparent data glasses do not rely on individual markers, but use markers that are used to position the entire overlay.

The implementation was done using the Unity 3D development environment (version 2021.3.0f1) and the NRSDK Unity package (version 1.10.2). In contrast to smartphones, the see-through data glasses enable 'signposting' by means of illuminated spheres, similar to a pick-by-light system, on the individual storage boxes. If a storage bin is not in the field of view, a directional arrow is displayed to help the subject find it. The data glasses are operated using a built-in hand tracking device. The display on the see-through data glasses is shown in Figure 4.

Figure 4: View through the data glasses with indicating of the marker for feedback that the application is calibrated (white corners on the tram photo) (left), arrow pointing to the position of the next part (green arrow pointing to the green dot) (centre), hand tracking and slightly shifted component (right).

2.4 Measurement

At the beginning of the study, the subjects' affinity for technology was measured using the TA-EG questionnaire. The questionnaire consists of 19 items on a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree) (Karrer et al. 2009). The negative items are negated and the means of the four scales 'enthusiasm', 'competence', 'negative attitude' and 'positive attitude' are formed. An overall mean is then calculated from these scales. The values of the TA-EG questionnaire range from 1 (very low affinity for technology) to 5 (very high affinity for technology). The TA-EG questionnaire is a validated and reliable instrument for assessing technology affinity across cognitive, emotional, and behavioural dimensions. Its multidimensional structure captures key aspects such as enthusiasm for technology, perceived competence, and scepticism. The scale demonstrates strong psychometric properties, including high intercorrelations between the items (0.722 to 0.843) and construct validity confirmed through factor analysis. Its broad applicability and ease of use make it suitable for diverse participant groups in both experimental and applied research settings. The TA-EG is therefore a scientifically grounded tool for evaluating technology affinity in study participants.

The assembly times (H1) and the number of assembly errors (H2, divided into 'wrong component' and 'incorrectly assembled component') were analysed using video recordings of the participants and from the internal cameras of the see-through data glasses. To determine the usability of the application (H3), the System Usability Scale (SUS) questionnaire was used (Brooke 1995). The SUS is a widely used, standardized instrument for assessing the perceived usability of interactive systems. It consists of ten items that capture key usability aspects such as effectiveness, efficiency, and user satisfaction. The SUS has been extensively validated across various domains and user populations, showing intercorrelations between all the selected items (± 0.7 to ±0.9) and sensitivity to usability differences. Its brevity, ease of administration, and strong empirical basis make it an efficient and robust tool for benchmarking system usability in research. The questionnaire consists of ten items on a five-point Likert scale ranging from 1 ('I strongly disagree') to 5 ('I strongly agree'). Half of the items are worded positively and the other half negatively. For scoring, the negatively worded items are negated and then all values are converted to a scale from zero to four. The sum of the items is multiplied by 2.5 (Brooke 1995). The result is on a scale from 0 to 100, where 0 means very bad and 100 means very good usability.

The subjects' strain (H4) was measured using the NASA TLX questionnaire (Hart and Staveland 1988). The questionnaire consists of a 20-point scale from 'low' to 'high' with six different subscales: 'mental demands', 'physical demands', 'time demands', 'performance', 'effort' and 'frustration'. Several pairwise comparisons are then made to indicate which item was more important for the task. Finally, an overall score is given between 0 (no strain) and 100 (extreme strain). Empirical studies have demonstrated its construct validity, sensitivity to workload variation, and applicability across domains such as aviation, healthcare, and human computer interfaces. Hart (2006) emphasized its high diagnostic value, enabling researchers to isolate specific sources of workload.

2.5 Experimental setup

NREAL Light see-through data glasses provide six degrees of freedom visualisation. The glasses have a display resolution of 1080p per eye, a brightness of 1000 nits and a field of view (FoV) of 52°. It also has three cameras: two greyscale cameras with a resolution of 640p x 480p and a FoV of 120° and one RGB camera with a resolution of 2592p x 1944p and a FoV of 74°. The glasses have a compact form factor and are reminiscent of slightly larger sunglasses (see Figure 5).

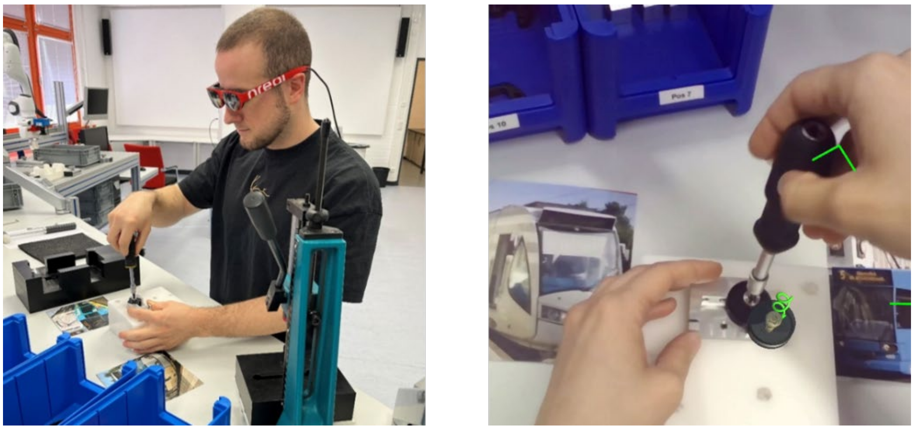

Figure 5: Test person during assembly of the emergency door release handle with the see-through data glasses

The compact form is achieved by the battery and processor being stored in a separate housing. The housing is connected to the camera via a cable and has a touch controller, which is not required due to the hand tracking used.

2.6 Experimental procedure

At the beginning of the experiment, which followed a between-subjects design, subjects were informed about the content and procedure of the study and signed an informed consent form including a privacy statement. The study began with the completion of a demographic questionnaire, which included information on age, gender, visual aid and previous experience with AR applications. Participants were then introduced to the use of the see-through data glasses using hand gestures and scanning a marker to position the application. After any unanswered questions had been clarified, the assembly task began, in which five emergency handles had to be assembled using the same test setup as in the previous study. The five assembly runs were performed immediately one after the other. The experimenter observed and used a sign with the words 'wrong component used' or 'wrong component assembled'. After the five assembly runs, the subjects completed the TA-EG, SUS and NASA-TLX questionnaires and had the opportunity to give feedback on the instructions used.

2.7 Sample

The see-through data glasses were used by eight subjects who had no previous experience of manually assembling a complex component. Unlike the previous sample, they did not receive any technical training. Two females and six males participated with an average age of 28.1 years ($SD = 3.2$ years). The smartphone users from the previous study (8 male) were on average 19.3 years old ($SD = 1.7$ years). A two-tailed unpaired t-test between the two groups, tested for normal distribution with the Shapiro-Wilk test and for homogeneity of variance with the Levene test, showed a significant difference in the age of the subjects ($t(14,00) = 5.741$; $p < 0.001$). No significant group differences were found in the average TA-EG values between the see-through data glasses ($M = 3.79$, $SD = 0.22$) and smartphone users ($M = 3.86$, $SD = 0.45$) ($U = 22.00$, $Z = -1.05$, $p = 0.328$). As these data are not normally distributed, the Mann-Whitney U-test was performed.

2.8 Results

Prior to analysis, all data were tested for normal distribution using the Shapiro-Wilk test and for homogeneity of variance using the Levene test. Either a t-test or an analysis of variance or Welch's t-test for independent samples was performed. The assembly times of the five runs are shown in Figure 6. For hypothesis H1, the differences in assembly times between the see-through data glasses and the smartphone group were analysed. For the sake of clarity, the values for the paper instructions are not shown here. In terms of initial ($t(14,00) =$

3.755; p = 0.002) and total (t(14,00) = 2.770; p = 0.015) duration, the paper instructions were on average 8.53 min (SD = 1.31 min) and 24.98 min (SD = 3.43 min) faster than the see-through data glasses, respectively.

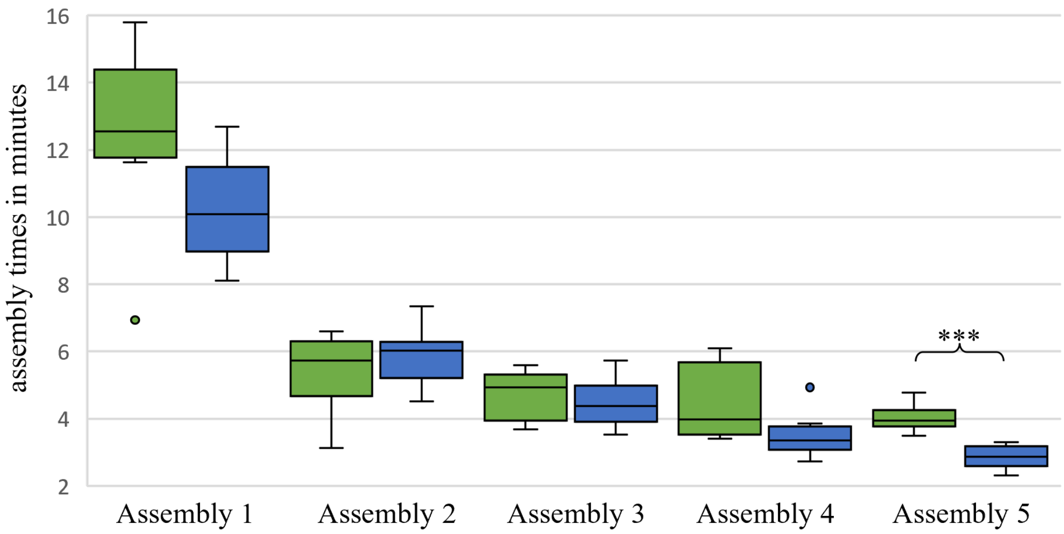

Figure 6: Box plots of assembly times for the see-through data glasses group (green) and the smartphone group (blue) (Funk and Schmidt 2020) grouped by assembly passes

Table 1 shows the means and standard deviations as well as the results of the t-test and the Welch's t-test, as there is no equality of variance in assembly 4.

Assembly passes	**See-through data glasses**	**Smartphone (Funk and Schmidt 2020)**	**T-test or Welch's t-test**
	M [min] (SD [min])		
Assembly 1	12,44 (2,63)	10,16 (1,52)	t(14,00) = 2,12; p = 0,053
Assembly 2	5,37 (1,14)	5,89 (0,85)	t(12,99) = -1,05; p = 0,312
Assembly 3	4,71 (0,74)	4,46 (0,70)	t(14,00) = 0,68; p = 0,507
Assembly 4	4,45 (1,10)	3,50 (0,67)	t(11,52) = 2,09; p = 0,060
Assembly 5	4,02 (0,39)	2,85 (0,34)	t(14,00) = 6,42; p < 0,001
total duration	30,98 (5,09)	26,88 (3,06)	t(14,00) = 1,957; p = 0,071

Table 1: Means and standard deviation of assembly times for the see-through data glasses and smartphone (Funk and Schmidt 2020) groups over five assembly passes and test results.

Regarding hypothesis H2, it is tested whether the number of errors differs according to the type of instruction used. The video recordings were analysed to determine the number of errors per type of instruction. The see-through data glasses group made an average of 3.38 errors (SD = 1.06 errors) while the smartphone group made an average of 3.13 errors (SD = 1.13 errors) (Funk and Schmidt 2020). The t-test showed no significant differences (t(14,00) = 0.457; p = 0.655). Figure 7 shows the average assembly errors of the five passes.

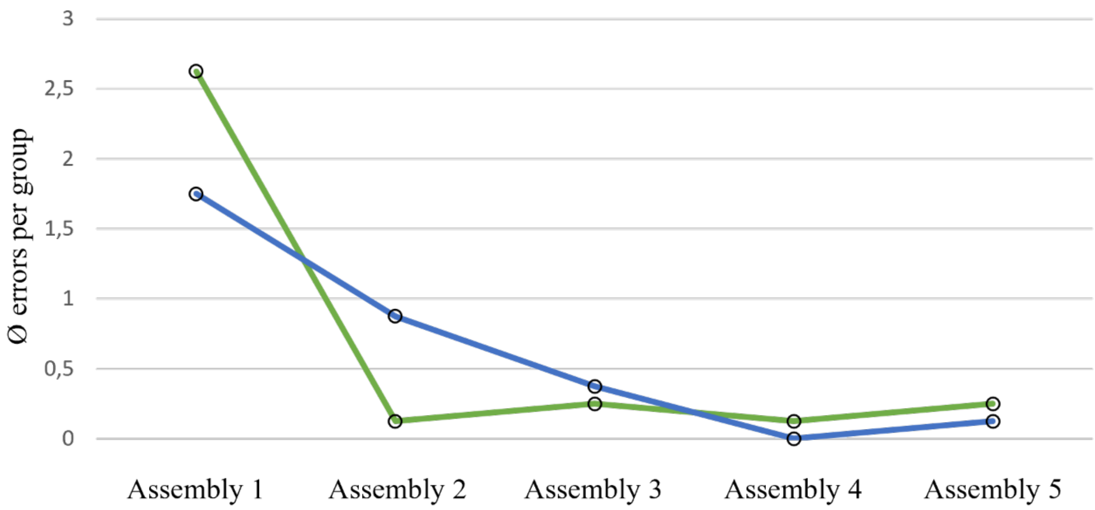

Figure 7: Average assembly errors of the see-through data glasses (green) and smartphone group (blue) (Funk and Schmidt 2020) over the assembly passes

Hypotheses H3 (usability) and H4 (strain) examine the extent to which the type of instruction – see-through data glasses, smartphone and paper – has an effect. The results are shown in Figure 8.

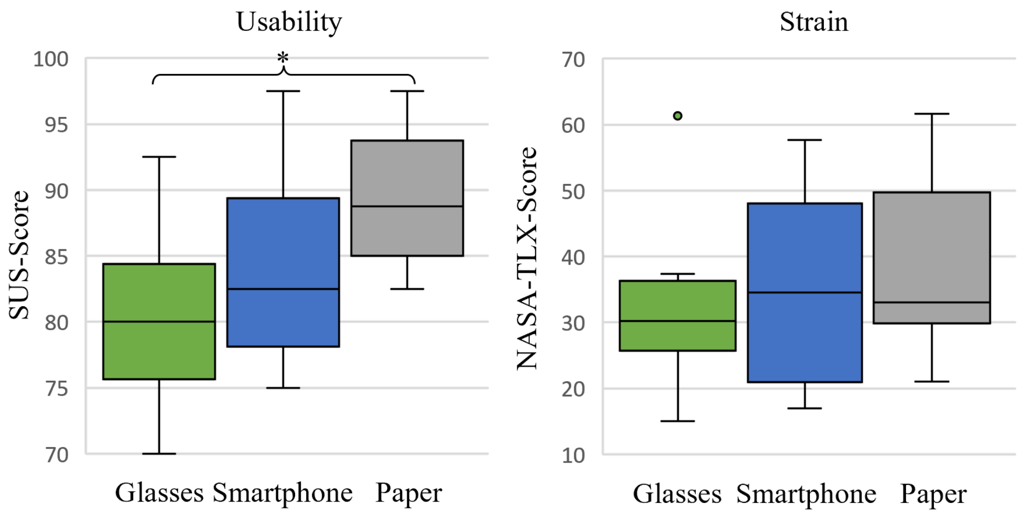

Figure 8: Usability (SUS) (left) and strain (NASA-TLX) (right)

An analysis of variance was used to test whether there were differences in usability and strain between the three groups. The data for each group were normally distributed (Shapiro-Wilk test, p > 0.05) and homogeneity of variance was confirmed by the Levene test (p >

DOI: 10.57813/eleed.vi16.256.g450

0.05). The average usability, calculated using the SUS, showed statistically significant differences ($F(2,21) = 3.63$, $p = 0.044$) regarding the average usability of the see-through data glasses group ($M = 80.31$, $SD = 6.87$), the smartphone group ($M = 84.06$, $SD = 7.31$) (Funk and Schmidt 2020) and the paper group ($M = 89.06$, $SD = 5.16$) (Funk and Schmidt 2020). The Tukey post hoc test showed a significant difference in SUS scores between the see-through data glasses and paper. The mean strain measured with the NASA-TLX was for the group using see-through data glasses $M = 32.62$, $SD = 13.35$, for the group using the smartphone $M = 34.70$, $SD = 14.53$ (Funk and Schmidt 2020) and for the group using paper $M = 37.37$, $SD = 13.61$ (Funk and Schmidt 2020). These differences in strain levels for the different types of instructions are not statistically significant ($F(2,21) = 0.237$, $p = 0.791$).

After completing the assembly task, the subjects were interviewed about their impressions of the instructional method used. The subjects' statements were recorded in bullet points and then categorised into positive and negative aspects of the instructional method in a table.

In the see-through data glasses group, the limited comfort of the see-through data glasses was mentioned as an inconvenience, and the fact that it was not possible for people who needed glasses to use the see-through data glasses was also mentioned as a problem. It is possible to use special glasses for spectacle wearers, but unfortunately, they were not available during the study. All spectacle wearers wore contact lenses during the trial. In terms of usability, it was criticized that sometimes the overlays were not transparent enough and the overlay hid the mounting area. Some models were considered to be too small, or the overlays were partially misaligned. During the various assembly steps, the instructions were considered to be less useful, which meant that assembly became cumbersome after the third step.

On the positive side, the assembly instructions were mentioned as being well placed and the actual positioning of the 3D objects helped with accurate assembly. The instructions were also mentioned for their intuitive use. Additionally, the instructions gave people a greater sense of security during the assembly process, as well as the fact that they could assemble at their own pace. All in all, it was found to be enjoyable and engaging.

In the smartphone group, the fact that the smartphone takes up one hand during use was mentioned as an inconvenience. It is also difficult to place the smartphone on the assembly station. The use of the smartphone in assembly was described as taking some getting used to. Other comments related to the technical challenges of marker-based AR applications. The sometimes lengthy time taken to recognise a marker was mentioned. It was criticised that the displayed content disappeared as soon as the smartphone was put down for assembly. In addition to the virtual 3D models of the components, this particularly affects the display of the item numbers of the parts storages. When the smartphone was picked up again, the markers had to be recognised again to retrieve the content.

In particular, the three-dimensional display of the components was mentioned as positive and very helpful. The positional accuracy of the 3D models on the workbench was seen as an advantage. The AR visualisation with 3D models was preferred to the usual 2D illustrations of models or photos of components. The ability to view the models of the components from different angles through different camera positions was also mentioned positively. The design of the AR instructions was described as clear, and the small amount of text combined with many 3D models was perceived as good. The fact that only the necessary information was displayed for each work step was also praised. Table 2 summarises the statements.

	Positive Statements	**Negative Statements**
See-through data glasses	Well-placed assembly instructions for easy navigation	Overlays are partially misaligned
	Correct positioning of 3D objects for accurate assembly	Limited wearing comfort
	Intuitive instructions for a smooth user experience	Overlays cover the mounting area, affecting usability
	Greater peace of mind during assembly with the ability to switch assembly steps at your own pace	Not suitable for eyeglass wearers
	Well-organized and clear assembly instructions	Some models are too small
	The assembly process was enjoyable and engaging	Instructions are helpful initially, but become cumbersome after repeated use
Smartphone (Funk and Schmidt 2020)	Three-dimensional representation of the components	Smartphone is perceived as a nuisance: one hand occupied
	Specification of the position numbers	Smartphone is perceived as a nuisance: Laying it down is complicated
	Well-structured layout of the instructions; small amounts of text	Smartphone usage in assembly takes some time to get used to
	Interactive use of the cell phone, models can be viewed from different sides	Marker recognition sometimes takes a long time
	True-to-position representation of the virtual objects on the assembly table	Markers must be rescanned after the phone was laid down
	AR visualization with 3D-models is better than using 2D-illustrations of 3D models or photos	Contents disappear from screen when the marker is not in the cameras field of view
	Only currently needed information are displayed	

Table 2: Positive and negative interview statements after assembly with see-through data glasses and smartphone (Funk and Schmidt 2020)

3. Discussion and Conclusion

When comparing the values of the AR instructions, there is a tendency for the group with data glasses to be slower than the smartphone group. A possible explanation could be that - in contrast to Hořejší, for example - there was no support in the form of additional information (Hořejší 2015). It can be assumed that the smartphone group's time advantage is due to users’ familiarity with the device. In contrast, the see-through data glasses are still relatively unfamiliar, and the technology is not yet fully mature. This is also reflected in lower usability ratings. Positional accuracy could have played an important role in speed. Another limitation was the fact that the sample for the instructions for the see-through data glasses did not have the same experience in manual assembly of components as industrial mechanics in training.

The results do not allow clear statements to be made about the errors. The group using the see-through data glasses made more errors in the first round, but the same number or even fewer errors in the other rounds. The average total number of errors was comparable. It could be suggested that the see-through data glasses were more effective after a longer period of familiarisation. The usability of both AR applications was rated as 'good', while the paper support was rated as 'excellent' (Bangor et al. 2009). The significantly worse usability of the see-through data glasses compared to the paper instructions suggests that the see-through data glasses AR application has not yet reached the maturity level of a paper manual. However, the average subjective strain with the see-through data glasses (32.62) is lower than the smartphone group (34.70) and the paper manual (37.37), although no significant differences were found between the groups. The results of other studies were used to categorise the strain values: In a meta-analysis, the NASA TLX values of 237 scientific studies with a total of 1173 data sets were evaluated. The median of all values is 49.93. 25% of the values are below 36.77 (Grier 2015). This means that the values can be assigned to a rather low level of strain.

In summary, there is a tendency towards poorer usability when using AR instructions (possibly due to the technical maturity of the hardware and technical sophistication of the hardware and software) and lower strain; the lower strain is in line with Buchner et al. (2022). This shows the potential of instructions with AR see-through data glasses, but the status quo is not yet sufficient to completely replace conventional assembly instructions. Particularly in view of the need for speech-accessible training methods for demanding assembly tasks, which are more difficult to implement with paper instructions, work should continue on frameworks for the simple implementation of assembly training as the market penetration of smart glasses increases and they become more widespread.

The increasingly affordable technology of see-through data glasses, coupled with more and more tracking methods, could be a useful alternative in assembly. The next steps should be to make tracking and positioning more accurate and to improve the maturity of instructions for AR see-through data glasses. One possibility is to use image recognition to guide the tracking directly to the assembly blocks and parts of the emergency handle.

Work is underway to improve the tracking of 3D objects: Currently in a beta stage is the state based model target tracking which allows a physical object to be tracked through different stages of assembly, for instance, when a part is placed in the assembly block and is in the correct position, the software recognises the part and moves on to the next step (Vuforia 2025). This would save time during the assembly process by automatically switching to the next step. Combined with a timer, the assembly instructions would only be displayed when the worker is struggling. This would allow for more accurate tracking and would not be dependent on pre-defined assembly fixtures and steps. This would be desirable, especially for implementation in real operations.

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