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The acceptance of smart glasses used as side-by-side instructions for complex assembly tasks is highly dependent on the device model

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ABSTRACT

Introduction: Smart glasses have recently been tested for assembly tasks to tackle the increasing demand for customized complex products. This study investigated the acceptance aspects of smart-eyewear devices under controlled laboratory conditions. Perceived usefulness (SUS), subjective strain (NASA-TLX), ergonomics, and user experience induced by working with different binocular smart glasses and a tablet were compared in a within-subjects design.
Methods: 18 (29.61 ± 11.4 yrs) took part in this study. All participants had to complete a complex construction task realized by a toy model consisting of 75 pieces. Two different smart glasses and a tablet were used to provide the participants with visual instructions. After each assembly task, various questionnaires were completed. Repeated measures ANOVA was conducted to compare the dependent variables subjective strain, system usability, and total time between the three-instruction media.
Results: The tablet was rated as the most useful, but there was also a significant difference between the two smart glasses. Descriptive analysis of the ergonomics and user interface constructs confirms the big model-specific differences between the smart glasses. Subjective strain and total time were the lowest on average for the tablet.
Conclusion: The observed effects presented in this study are dependent on the hardware implementation. This means the results of other acceptance studies using binocular smart glasses must be thoroughly assessed with a strong emphasis on the model type and should not be generally related to binocular smart glasses in the assembly industry.

1. Introduction

Smart glasses have been tested in the industry as part of pilot studies, mainly in the fields of logistics and assembly in large companies (Glockner et al., 2014). They have also been used under natural conditions at assembly workplaces and picking workstations (Berkemeier et al., 2017; Borisov et al., 2018; Friemert et al., 2016; Gross et al., 2018; Kolla et al., 2021; Smith et al., 2021). The effects of smart glasses on workers can be studied from different perspectives (e.g., efficiency, electromagnetic radiation, eye strain). The acceptance of smart glasses has been investigated in numerous publications.

The term acceptance deals with the concepts of behavior, belief, intention, attitude, and the relationships between them (Fishbein and Ajzen, 1977). The methodology used to capture the acceptance of new work tools was similar in all studies. Existing questionnaires (e.g., TAM) (Terhoeven et al., 2018) or modified versions (Rauschnabel and Ro, 2016) were used. The "Technology Acceptance Model" (TAM) is based on an attempt to explain a user's acceptance and behavior (Schuster et al., 2021). The model focuses on perceived usefulness (PU) and perceived ease of use (PEU). Both components affect the acceptance of using a technological system. Perceived usefulness is the likelihood that a user's action will improve because of using the system.

Some studies examined the acceptance of smart glasses in the general population (Basoglu et al., 2017; Rauschnabel and Ro, 2016), while others conducted research with students (Koelle et al., 2017). Very few analyses were performed with professional staff in companies (Borisov et al., 2018; Terhoeven et al., 2018) or experts (Koelle et al., 2017). In addition, internet-based surveys (Basoglu et al., 2017) and expert

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interviews (Koelle et al., 2017; Wille et al., 2014) were conducted. Wearing comfort, related to the weight and fixation of the smart glasses on the head, is also frequently criticized (Gabbard et al., 2018; Rejeb et al., 2021; Wille et al., 2014). Flexible display positioning combined with high display resolution is reported as a desideratum (Koelle et al., 2017). Furthermore, significant effort has been spent on analyzing ergonomic information presentation. As a result of a study by Kim et al. (2019), it was recommended that the information on the display should be presented primarily in a graphics-based manner. Koelle et al. (2017) did not see a measurable change in the predominantly negative attitudes toward smart glasses during a multi-year study. These results were not generalizable because the participants in the study were mainly students. The additional survey of 51 experts showed that increased acceptance of smart glasses is expected by 2026. Usefulness, functionality, and usability were identified as the most critical factors for long-term acceptance. According to this study, existing usability problems must be solved using novel interaction methods and visualization techniques. In their research, Terhoeven et al. (2018) found that the acceptance of smart glasses depends on the specific application. While the workers predominantly negatively assessed smart glasses in the use case "picking," the use case "assembly" assessments were relatively positive. Wille et al. (2014) also found that the new technology assessment depends on the respondents' affinity for technology. Other studies have made evaluative comparisons between different display types (Borisov et al., 2018; Gross et al., 2018; Sedighi et al., 2018; Wille et al., 2014). In no study did smart glasses outperform other work tools. Gross et al. (2018) compared a tablet with two different smart glasses (monocular and binocular). The tablet was rated the best and the binocular smart glasses the worst. In the study by Sedighi et al. (2018), smart glasses were compared with smartphones and paper-based systems. The following differences became evident: (i) the smartphone was preferred over the paper-based system and the smart glasses, (ii) the second most preferred display was the paper-based system, and (iii) the least preferred device was the smart glasses. The negative responses in terms of usefulness were primarily related to the design of the smart glasses and not to the quality of the display. There was criticism that the weight of the glasses was uncomfortable and challenging to balance. Regarding the display, the smart glasses were rated as the most useful. This positive assessment regarding usefulness indicates that the participants appreciate having their hands free and the screen at eye level.

Different display types and HMIs were also compared and evaluated in the field test by Borisov et al. (2018). The smartphone received the highest marks because its lightweight and ergonomic design make it a suitable product inspection tool. Nevertheless, the authors see a high potential for the future use of smart glasses in an industrial environment. In their view, a prerequisite for improved acceptance is a comprehensive response to the health and hygiene issues that inevitably arise when using smart glasses. Wearable devices (especially smart glasses) need to be very well designed and engineered, i.e., ergonomic hardware, software, and hygiene, to satisfy workers in a production context. Rodriguez et al. (2021) investigated whether performance and usability differ when instructions for a building task are presented on digital glasses or paper. 63 participants completed one of three versions of a building task using LEGO bricks, instructions on the form, step-by-step text instructions via smart glasses, and step-by-step text and auditory instructions via smart glasses. The results show that the tasks were completed faster with the paper instructions compared to the two versions of the instructions via the smart glasses. Further studies are recommended to investigate whether effectiveness and ease of use might depend on the complexity of the task, the device, and how the information is presented.

This study investigated the effects of smart glasses on the acceptance of complex assembly tasks. In addition, the impact of using each display on cognitive load, ergonomics, and user experience was investigated using various questionnaires. It was hypothesized that acceptance in terms of perceived usefulness would differ between the three assistance systems (H1) and that subjective strain would differ between systems (H2). Based on the literature listed, the final research hypothesis (H3) was that there are differences in efficiency between the three instruction systems. A laboratory study was conducted in which employees from the assembly industry had to repeatedly complete complex design tasks using three different digital work tools to answer these research hypotheses.

2. Methods

2.1. Participants

18 participants voluntarily participated in this study. The ethics review board of the Koblenz University of Applied Sciences approved the study. Before the measurements, all participants signed written informed consent. The age of the participants (16 men, 2 women) ranged from 21 to 58 years, with a mean of 29.61 $\pm$ 11.4 years. Their mean height was 180.5 $\pm$ 7.6 cm, and their mean weight was 90.2 $\pm$ 18.7 kg. Three participants (16.6%) reported a pre-existing condition, and ten candidates (55.5%) reported a visual impairment. However, all participants stated that they could perform the tasks without glasses. Fifteen participants (83.3%) were right-handed, two participants (11.1%) were left-handed, and one participant (5.5%) was ambidextrous. All 18 candidates reported German as their native language, of which seven candidates (38.8%) were in education at the time of the study, and 11 candidates (61.1%) were employed. Experience in assembly was reported by 18 participants (100%) with an average duration of 5.1 $\pm$ 7.5 years. Zero participants had previous experience with smart glasses as an assembly aid. The average technology affinity of the participant collective was 69.73 $\pm$ 8.87, scoring points on a scale of 0 (minimum) to 100 (maximum).

2.2. Experimental design and task description

This study investigated two different binocular smart glasses and a tablet as an established reference system in a within-subjects design. The two smart glasses (Microsoft HoloLens, 1st generation, and the Magic Leap One) were compared with the Lenovo Tab M10 tablet as the reference system. The design task consisted of assembling miniature models from the Eitech Company (Fig. 1) from individual parts. Each participant completed one task with each medium.

The setup corresponded to a model replica of a standardized assembly workstation (Fig. 2).

A height-adjustable assembly table was equipped with four visual storage boxes and the necessary tools in a well-lit and separate laboratory area. The boxes were filled with the respective components for the construction task in multiples and sorted by component type. The visual storage boxes were located on the front side of the table. The test series took place in the Laboratory for Biomechanics and Ergonomics at the Koblenz University of Applied Sciences in Remagen.

At the beginning of the measurement day, the participants were introduced to their tasks. After filling out the necessary forms required by data protection law and a socio-demographic questionnaire, a design task was performed with the three assistance systems. After completing the work with one implement, a questionnaire was filled out, and a 20-min break was taken. The process was then repeated with the other work tools. The Latin square scheme was used to randomize the order of the work tools and the miniature models. One task consisted of four subtasks. The model's current state was illustrated with the help of a schematic drawing. Newly added components were projected onto the current state of the model in exploded view and displayed in orange (Fig. 2). Speech and gesture recognition algorithms were used to select the individual work steps. In addition, the models could be rotated, scaled, and positioned in space. Before the assembly task started, a trial measurement was performed with each assistance system to familiarize the user with the medium. The time and errors of each task were

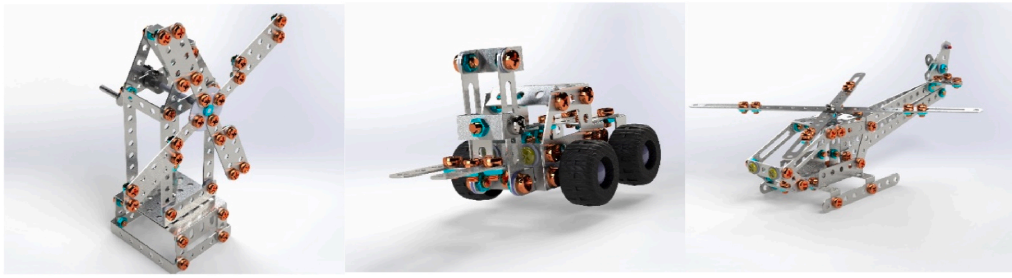

Fig. 1. Illustration of the three different construction models: Windmill (left), forklift (center), and helicopter (right).

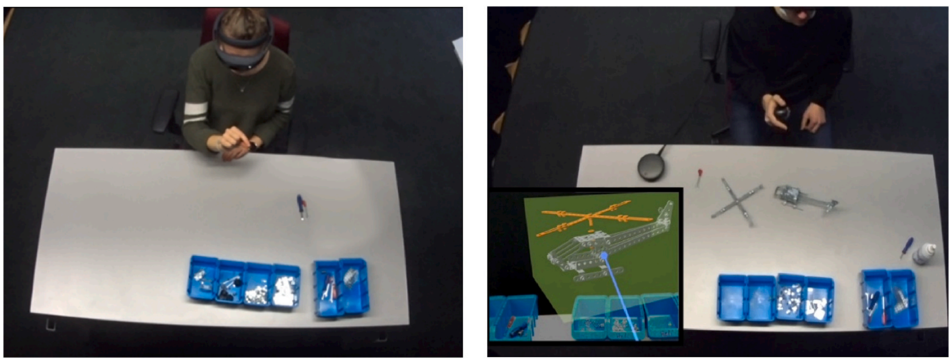

Fig. 2. Representation of the assembly workplace. The participants completed each of the four construction steps within a construction task using one of the three instruction media described in the text, using the Microsoft HoloLens (left) and Magic Leap One (right). The participant's field of view is illustrated in the bottom left corner. The new components to be added are shown in orange. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

recorded.

2.3. Questionnaires

The acceptance of the instruction media was surveyed with the aid of various questionnaires. In total, each respondent answered five questionnaires. In addition to an introductory and a concluding questionnaire, one questionnaire was responded to after each completed assembly task with an instruction medium. The initial questionnaire included the following constructs: Sociodemographic Data, Assembly Experience, Physical Limitations, and Technology Affinity (TAEG) (Karrer-Gauß et al., 2009). All constructs, except for TAEG, were created following Wille (2016). The post assembly task questionnaires consisted of four constructs. These included the NASA Task Load Index (NASA-TLX) (Hart and Staveland, 1988), the System Usability Scale (SUS) (Brooke, 1996), and the system-specific constructs of ergonomics and user experience (Table 1). The final questionnaire contained the two constructs "opportunities" and "risks" of smart glasses in the assembly industry. The items of these constructs corresponded to the Likert-type were designed following Günthner et al. (2009) and contained a unique ID composed of the initial letter of the construct and the number of the question. The questionnaires were collected exclusively in digital form.

Table 1
Presentation of the questionnaire ergonomics and user experience of smart glasses. The questionnaire was conducted after each work with an instructional medium. Each question is indicated by its ID. Response options were based on a 5-point Likert scale ranging from "strongly agree" to "strongly disagree".

Construct	ID	Question
Ergonomics	E1	The assistance system can be adjusted to suit short-term carrying.
	E2	The assistance system can be adjusted to suit long-term carrying.
	E3	The weight distribution of the assistance system is pleasant in the short term.
	E4	The weight distribution of the assistance system is pleasant in the short term.
User-Experience	UE1	I quickly got used to working with the medium.
	UE2	I find dealing with the medium simple.
	UE3	The medium always recognizes my input immediately.
	UE4	The components can be positioned well.
	UE5	The components can be rotated well.
	UE6	The components can be scaled well.

2.4. Data analysis

Data analysis was performed in Python (Software Spyder, Version 3.7.5, Python Software Foundation, Delaware, USA). The scores of the construct SUS were determined and scaled to a range from 0 to 100. This corresponds to the value range of the NASA-TLX. For correlation tests, mean scores were calculated for each participant.

2.5. Statistics

Statistical analysis was performed using R (version 1.4.1717, RStudio, Inc., Boston, MA). The introductory questionnaire, the final questionnaire, the constructs ergonomics, user experience, and the number of errors were analyzed descriptively. The mean values of the NASA-TLX, SUS constructs, and the total times were evaluated using a one-way repeated measures ANOVA. The normal distribution of the residuals was visually audited via Q–Q (quantile-quantile) plots. Boxplots were used to detect outliers, and sphericity was analyzed through the Mauchly test ($\alpha = 0.05$) with a Greenhouse–Geisser correction, if necessary. The statistical significance level was 0.05, and posthoc pairwise comparisons were made with Student's t-test. The Bonferroni alpha error correction was applied to account for multiple comparisons. The Spearman correlation method ($\alpha = 0.05$) examined correlations for various parameters. For this purpose, technology affinity, age, and arithmetic mean values of NASA-TLX and SUS- score was used.

3. Results

3.1. Time and errors

With the tablet (mean and SD: 1501.33s ± 435.71s), the assembly task was completed fastest on average, and the Microsoft HoloLens (1753.44s ± 465.13s) was the slowest. The Magic Leap (1673.44s ± 367.01s) was between the other two systems in terms of time. The repeated measures ANOVA did not reveal a significant difference between the assistance systems with respect to total time (F (2,34) = 2.78, p = 0.076, $\eta^2p = 0.141$). The 18 participants assembled 4068 components during the measurements, and 20 errors were detected. On average, one participant made 0.37 ± 0.65 errors per order. On average, the participants made more errors with the tablet (0.5, ±0.85) than with the Microsoft HoloLens (0.38 ± 0.6) and the Magic Leap (0.22 ± 0.42).

3.2. Subjective strain

The distribution, the mean, and the standard deviation of the NASA-TLX scores for each condition are shown in Fig. 3. The subjective strain after working with the Microsoft HoloLens was highest (mean and SD: 36.98 ± 20.67) in comparison after working with the Magic Leap One (29.48 ± 16.31) and the tablet (26.35 ± 14.42).

Statistical analysis revealed a significant difference between the three different conditions, F (1.52, 25.88) = 3.79, p = 0.047, $\eta_p^2 = 0.182$. However, posthoc analyses show no significant differences between the different media (Table 2).

3.3. System usability

The distribution, the mean, and the standard deviation of the NASA-TLX scores for each condition are shown in Fig. 4. The perceived subjective usefulness of a system was highest after working with the tablet (mean and SD: 93.19 ± 7.51) in comparison with the Magic Leap One (79.72 ± 13.69) and the Microsoft HoloLens (59.17 ± 24.10). The one-way repeated measures ANOVA revealed a statistically significant difference between the three conditions, F (1.30, 22.12) = 25.04, $p < 0.001$, $\eta_p^2 = 0.596$. Using the Tablet for assembly tasks led to significantly higher perceived usefulness values than the Microsoft HoloLens and the Magic Leap One (Table 1). Furthermore, the system usability score was significantly higher for the Magic Leap One than for the Microsoft HoloLens (Table 1).

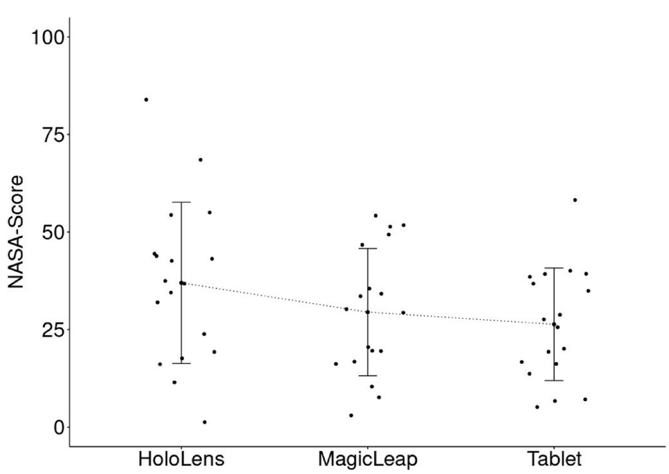

Fig. 3. Visualization of the distribution, the mean, and standard deviation of subjective strain (NASA-TLX) for the three experimental conditions: Microsoft HoloLens, Magic Leap One, and Tablet. The data points represent the score achieved by the respective participant. Statistically significant differences are indicated with asterisks (*p < 0.05, **p < 0.01, ***p < 0.001, ****p < 0.0001).

Table 2
Results for the post hoc analyses between Microsoft HoloLens (HL), Magic Leap One (ML), and Lenovo Tablet (TAB) on changes in subjective strain (NASA-TLX-Score) and perceived usefulness of a system (SUS-Score). P values are reported with the mean difference and 95% confidence interval. Bold font highlighting significant effects (p < 0.05).

Dependent Variables	HL - ML	HL - TAB	ML - TAB
NASA-TLX-Score	p = 0.348, 7.51, 95%-CI [-2.07, 17.10]	p = 0.086, 10.64, 95%-CI [1.24, 20.04]	p = 0.756, 3.125, 95%-CI [-2.43, 8.68]
SUS- Score	**p = 0.008, −20.56, 95%-CI [-32.89, -8.22]**	**p < 0.001, −34.03, 95%-CI [-45.53, -22.52]**	**p < 0.001, −13.47, 95%-CI [-18.84, -8.11]**

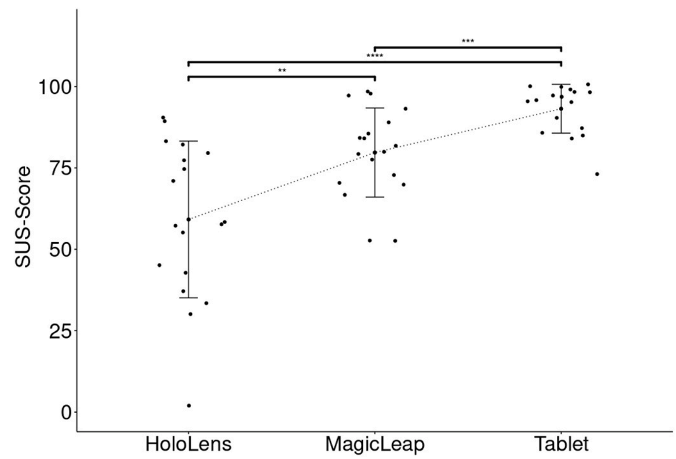

Fig. 4. Visualization of the distribution, the mean, and standard deviation of system usability scale (SUS) for the three experimental conditions: Microsoft HoloLens, Magic Leap One, and Tablet. The data points represent the score achieved by the respective participant. Statistically significant differences are indicated with asterisks (*p < 0.05, **p < 0.01, ***p < 0.001, ****p < 0.0001).

3.4. Correlations

Spearman-correlation analysis revealed a significant correlation between subjective strain (NASA- TLX) and perceived usefulness of a system (SUS) (ρ = −0.685, p = 0.002; Fig. 5) and no correlation between age of participants and SUS (ρ = 0.081, p = 0.748), and technology

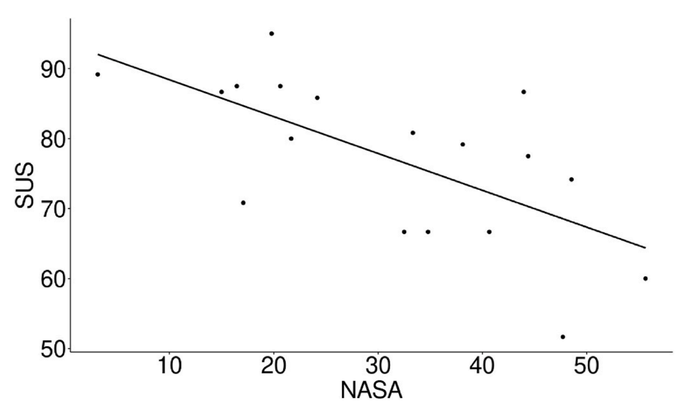

Fig. 5. The plot of the correlation between the parameters SUS and NASA-TLX. Perceived usefulness and cognitive load correlated strongly negatively with Spearman's ρ = −0.685, p = 0.002. The linear regression equation is y = 94 - 0.53x.

affinity of the participants (TAEG) and SUS (ρ = 0.203, p = 0.418).

3.5. Ergonomics

E1 and E2 (Fig. 6) show that participants reported lower comfort with the ergonomic adjustment options after working with the Microsoft HoloLens than the Magic Leap One, especially for more extended periods (E2). After working with the smart glasses, 15 participants (88.23%) agreed with statement E1. Six participants (33.33%) stated that the Magic Leap One could be adjusted appropriately for long-term wear, and only two participants (11.11%) disagreed with statement E2. In contrast, six participants (33.33%) do not believe that the HoloLens can be adjusted appropriately for long-term wear. Items E3 and E4 show that candidates reported lower ergonomic wearing comfort regarding the weight distribution of the smart glasses after working with the Microsoft HoloLens compared to the Magic Leap One. Thirteen participants (72.22%) disagreed with the statement that the weight distribution of the HoloLens is perceived as comfortable during long-term work (E4). In contrast, thirteen candidates agreed with statement E4 after working with the Magic Leap One.

3.6. User experience

UE1 to UE3 (Fig. 7) show that participants reported much lower satisfaction with the user experience after working with Microsoft HoloLens than with the Magic Leap One and the tablet instructions. Zero participants disagreed with statements UE1 to UE3 for Magic Leap and Tablet, which describe familiarization with the instructional medium (UE1), ease of use (UE2), and input recognition (UE3). In contrast, four participants (22.2%) disagreed with the statement UE1, five participants (27.7%) disagreed with statement UE2, and six candidates (33.3%) disagreed with statement UE3 after working with the Microsoft HoloLens. UE4 to UE6 indicate that candidates announced lower satisfaction with the Microsoft HoloLens than the Magic Leap and the tablet when interacting with the medium. None of the items are rated as unfavorable after working with the tablet. In contrast, the rotation of the components with the Microsoft HoloLens was rated as less satisfactory. Five participants (27.7%) disagreed with the statement that the pieces can be rotated well with the HoloLens.

3.7. Potential and risks

The increase in efficiency (C1) was assessed ambivalently (Fig. 8). Only one respondent (5.56%) strongly agreed with the statement that one works faster with smart glasses. Seven participants (38.89%) were neutral toward the statement, and six (33.33%) disagreed. Similar assessments were made regarding the prevention of errors (C2).

Adverse health consequences due to working with smart glasses (R1) were not seen as a risk by the participants. Eight candidates (44.44%) disagreed with this statement, and five participants (27.78) strongly disagreed. Only two participants (11.11%) agreed with the statement R1. Concerning the risk of distraction (R2), one participant (5.56%) strongly agreed that smart glasses distract while working. Seven participants (38.89%) disagreed with this statement, and three candidates (16.67%) strongly disagreed. Hygiene problems (R3) were also not considered to be a risk by the majority of participants (61.11%). Four participants (22.22%) were neutral towards this statement, and one participant (5.56%) agreed with the statement.

3.8. Concluding questionnaire

When asked which assistance system is preferred for assembly, the tablet was mentioned eleven times (61.11%) and the smart glasses seven times. In response to which of these two systems the participants would make the fewest errors in their estimation, the smart glasses were mentioned eight times (44.44%) and the tablet ten times (55.56%). Fifteen participants (83.33%) could imagine working with smart glasses and estimated the period of possible use as follows: The time window of two to 4 h was mentioned most frequently (50%), and four candidates (22.22%) would not like to work with smart glasses for more than 2 h a day, while two candidates (11.11%) could imagine working with smart glasses for four to 6 h. The Magic Leap One was mentioned sixteen times (88.89%) and the Microsoft HoloLens two times (11.11%) as preferred smart glasses. Sixteen respondents (88.89%) could imagine smart glasses becoming prevalent in the assembly process of the future.

4. Discussion

This study aimed to investigate the effects of smart glasses on the acceptance of industrial workers in complex assembly tasks. In addition, the impact of using each display on cognitive load, ergonomics, and user experience was investigated using various questionnaires. Furthermore, the efficiency parameters time and error were analyzed. The analysis of the perceived usefulness of an instructional medium (SUS) reflected significant differences between the three systems. This is consistent with our hypothesis (H1) that the use of different work tools impacts workers' acceptance of working with complex tasks. These general differences are coherent with the research findings of Kolla et al. (2021). However, the pairwise comparisons between the two smart glasses and the tablet seem to be of particular interest in our study. The tablet was rated the most

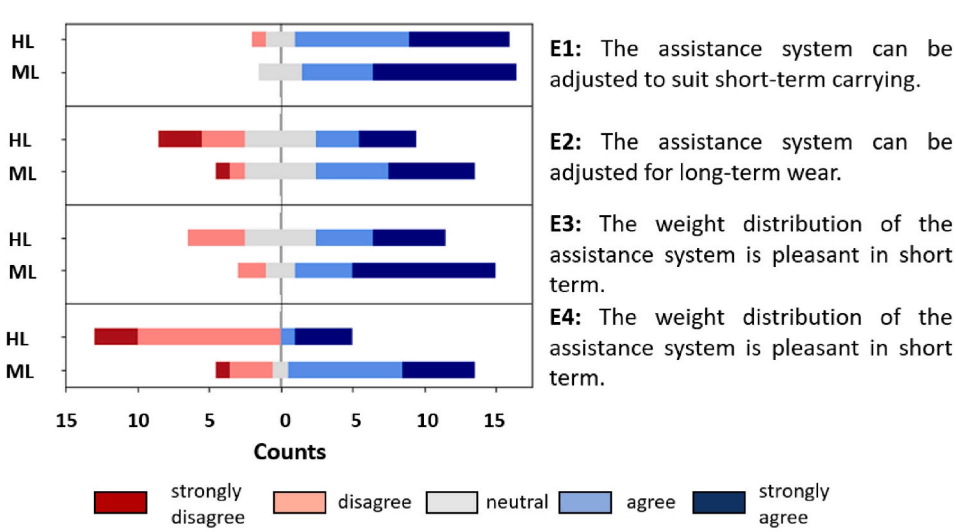

Fig. 6. The ergonomics of smart glasses according to the evaluation of the questionnaires. Each question is indicated by its ID. The answers of all 18 participants are represented by the bars, which correspond to a frequency distribution. The bars are zero-centered and color-coded due to the bipolar scale, as indicated in the legend. The abbreviations HL (HoloLens) and ML (Magic Leap) were introduced for simplification. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

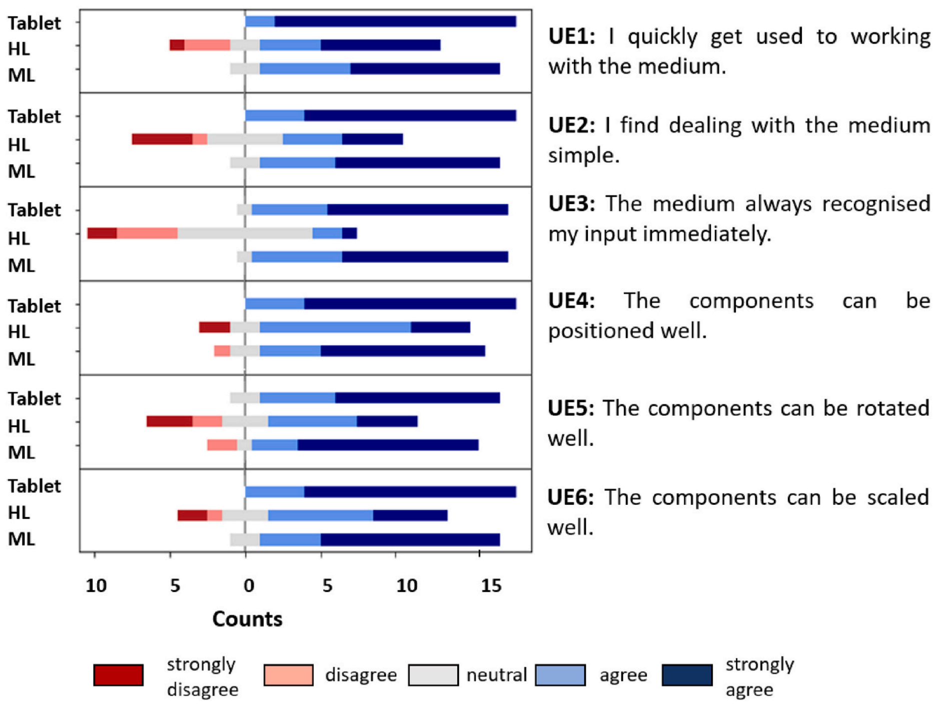

Fig. 7. The user experience of smart glasses according to the evaluation of the questionnaires. Each question is indicated by its ID. The answers of all 18 participants are represented by the bars, which correspond to a frequency distribution. The bars are zero-centered and color-coded due to the bipolar scale, as indicated in the legend. The abbreviations HL (HoloLens) and ML (Magic Leap) were introduced for simplification. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

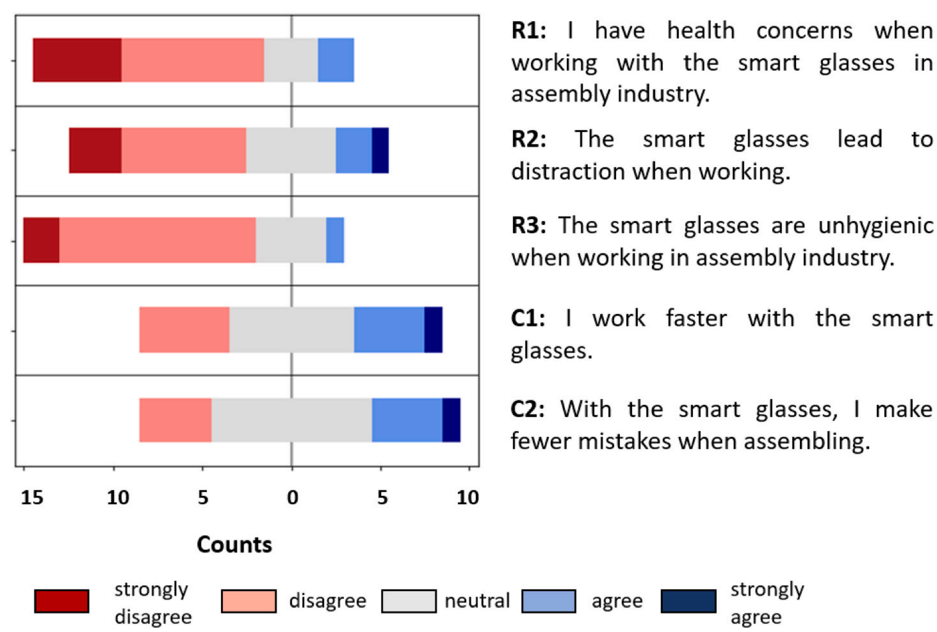

Fig. 8. The opportunities and risks of smart glasses according to the evaluation of the questionnaires. Each question is indicated by its ID. The answers of all 18 participants are represented by the bars, which correspond to a frequency distribution. The bars are zero-centered and color-coded due to the bipolar scale, as indicated in the legend. The abbreviations HL (HoloLens) and ML (Magic Leap) were introduced for simplification.

beneficial and the Microsoft HoloLens as the least helpful. These results are consistent with the study by Gross et al. (2018), who compared a tablet with two different types of smart glasses (monocular and binocular), and the tablet was rated best. These significant differences between the smart glasses models provide evidence that it is impossible to make a generalizable statement about smart glasses when considering their acceptance. According to the authors, it is urgent to evaluate each model individually from the different aspects. These observations tend to be supported by our specific questionnaire constructs of ergonomics and user experience. One crucial factor seems to be the way the user controls the HoloLens. As revealed by the user experience survey, its gesture control scored the worst. Six participants (33.33%) stated that input via gesture control was not consistently recognized immediately by the system, and five candidates (27.78%) said that they do not rate the handling of the Microsoft HoloLens as easy. Furthermore, the handling with the controller of the Magic Leap One was rated better than the gesture control of the Microsoft HoloLens (UX4-UX5). Since the tablet is perceived as an everyday object, handling may be more intuitive and requires less familiarization. According to Rejeb et al. (2021), ergonomics plays a predominant role in smart glasses opportunities. Examining the individual question items in more detail, the Microsoft HoloLens tended to be rated worse than the Magic Leap smart glasses

(E1-E6 & UE1-UE6). These observed effects are strongly dependent on the hardware implementation. In terms of ergonomics, our data support the assumption by Sedighi et al. (2018) that weight distribution seems to be important in terms of attention. Thirteen participants (72.22%) stated that the weight distribution of the HoloLens is uncomfortable during long-term work. Another possible cause could be the higher total weight of the HoloLens (579g) than the Magic Leap (316g).

The analysis of the subjective strain of an instructional medium reflected no significant differences between the three systems. Based on these results, we do not confirm our hypothesis (H2) and conclude that the use of smart glasses does not significantly impact subjective strain compared to a tablet. However, the NASA-TXL scores show slight differences between the two smart glasses and the tablet. The subjective stress is slightly lower after working with the tablet than with the two smart glasses, and we see a similar tendency as in Kolla et al. (2021). This study revealed a negative correlation between subjective strain and perceived usefulness ($\rho = -0.685$, $p = 0.002$). The higher cognitive strain seems to be associated with lower perceived usefulness. Consequently, due to the slight tendencies towards model dependency in subjective strain, we recommend conducting further studies with several different smart glasses models.

Based on our efficiency analysis, no significant evidence was found for an increase in efficiency of the smart glasses compared to the tablet. This leads to the conclusion that our hypothesis (H3) cannot be confirmed. However, on average, there were differences in total times between the two models of smart glasses and between the smart glasses and the tablet. For the tablet, the central tendency was to assemble the fastest and make the most errors. The mean values of the total times and the number of mistakes differed between Magic Leap and HoloLens in favor of Magic Leap. This indicates the relevance of the hardware implementation when selecting a pair of smart glasses for the assembly industry. In terms of efficiency (overall times and errors), our study thus provides ambivalent results for the evaluation of the efficiency of smart glasses in complex assembly tasks and confirms the consensus of previous studies (Borisov et al., 2018; Gross et al., 2018; Rodriguez et al., 2021; Sedighi et al., 2018; Wille et al., 2014; Smith et al., 2021).

According to our final questionnaire, most of the participants of the collective had a positive attitude towards the use of smart glasses in the assembly industry. Eight participants (50%) could imagine working with smart glasses for two to 4 h a day. According to our study, in contrast to Borisov et al. (2018), hygienic concerns are not a problem.

To sum up, our study showed that the selection of the model under the aspects of acceptance plays a significant role. We support Kolla et al. (2021) with their claim that especially the ergonomic characteristics underline the importance of the impact on the health and well-being of working with smart glasses. Therefore, more attention needs to minimizing mental workload to ensure better ergonomics. Thus, the ergonomics of smart glasses must be well suited for industrial activities, and designers should make the device more adaptable and compatible with other glasses. As a result, a collaboration between smart glasses designers and ergonomics experts is needed to ensure the successful use of the technology in logistics and assembly.

4.1. Study limitations

A few limitations of this study should be considered when interpreting the results. The participants performed the task in a sitting position. Thus, it must be further investigated if the same results can be found in a setup where the instruction systems must also be held in hand, and no stationary workstation is feasible. Additionally, only the effects of smart glasses after working for half an hour were analyzed. Hence, it is unclear whether the findings can be transferred to a setup where people work with the instruction systems for a significantly longer time. Therefore, based on our designed laboratory study, no clear forecast can be made about using natural assembly plants.

Another limitation of our study is the low consideration of the factor of visual impairment. In principle, only subjects who felt able to solve the tasks without visual aids were admitted. However, it could not be ensured that this was really the case and not just a socially desired reaction of the subjects in the test situation. It would also have been exciting to examine issues with a more extended assembly experience. Many of them were still in training, and our study only provides a limited clear statement on how experienced and older participants behave. In addition, thermal effects induced by smart glasses could impact the acceptance of smart glasses in the assembly industry. Further studies are required to clarify these relationships.

5. Conclusion

In this study, the difference in selected acceptance parameters and time and errors in construction tasks were investigated using three different instruction media (two binocular smart glasses and one tablet) under laboratory conditions. The hypothesis (H1) derived from the literature that the acceptance of assembly workers differs when working with different assistance systems is consistent with the results of our acceptance analysis. The observed effects presented in this study are dependent on the hardware implementation. This means the results of other acceptance studies using binocular smart glasses must be thoroughly assessed with a strong emphasis on the model type and should not be generally related to binocular smart glasses in the assembly industry. The data for the cognitive load analysis shows no significant differences between the three systems, which leads to the null hypothesis (H2) not being rejected. However, the mean values as a measure of central tendency provide small indications that hardware may play a cognitive load role. In terms of subjective strain and perceived usefulness, differences between the smart glasses and between the smart glasses and the tablet are evident. This could have a major impact on psychological stress and thus on long-term safety and health in the workplace. The efficiency analysis examined the hypothesis (H3) of whether there are differences in efficiency between the three systems. Through the statistical evaluation of the data, we conclude that smart glasses do not lead to a significant increase in efficiency.

An actual assembly workplace will almost certainly differ from our replicated laboratory workplace. In actual work environments, the potential of smart glasses in the *hands-free* area might become more apparent.

Author statement

Martin Laun: Methodology, software, formal analysis, investigation, data curation, writing- original draft, visualization. **Christian Czech:** software, investigation, visualization, writing- original draft. **Ulrich Hartmann:** conceptualization, resources, writing-review & editing, supervision, project administration, funding acquisition. **Claudia Terschüren:** writing-review & editing. **Volker Harth:** project administration, funding acquisition. **Kiros Karamanidis:** conceptualization, writing-review & editing. **Daniel Friemert:** conceptualization, validation, funding acquisition, writing - review &editing, project administration, supervision.

Availability of data and materials

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: University of Applied Sciences Koblenz reports financial support was provided by Employers' Liability Insurance Association for the Retail and Goods Distribution (BGHW).

References

Basoglu, N., Ok, A., Daim, T., 2017. What will it take to adopt smart glasses: a consumer choice-based review. Technol. Soc. 50, 50–56. https://doi.org/10.1016/j.techsoc.2017.04.005.

Berkemeier, L., Werning, S., Zobel, B., Ickerott, I., Thomas, O., October, 2017. The customer as service provider: acceptance and usability of smart glasses in self-service. HMD Prax. Wirtsch. 54 (5), 781–794. https://doi.org/10.1365/s40702-017-0342-1.

Borisov, N., Weyers, B., Kluge, A., 2018. Designing a human machine interface for quality assurance in car manufacturing: an attempt to address the "functionality versus user experience contradiction" in professional production environments. Adv. Hum. Comput. Interact. https://doi.org/10.1155/2018/9502692, 2018.

Brooke, J., 1996. SUS - a quick and dirty usability scale. Usability Eval Ind 189, 4–7. https://doi.org/10.1002/hbm.20701.

Fishbein, M., Ajzen, I., 1977. Belief, attitude, intention, and behavior: an introduction to theory and research. Philos. Rhetor. 10 (2).

Friemert, D., Ellegast, R., Hartmann, U., 2016. Data glasses for picking workplaces. In: International Conference on HCI in Business, Government, and Organizations. Springer, Toronto, pp. 281–289.

Gabbard, J., Mehra, D., Swann, J., 2018. Effects of AR display context switching and focal distance switching on human performance. In: IEEE (Ed.), IEEE Transactions on Visualization and Computer Graphics. https://doi.org/10.1109/TVCG.2018.2832633.

Glockner, H., Jannek, K., Mahn, J., Theis, B., 2014. Augmented reality in logistics, DHL research 2014. Retrieved on February 24, 2019, from. http://www.delivering-tomorrow.de/wp-content/uploads/2015/08/dhl-report-augmented-reality-2014.pdf.

Gross, B., Bretschneider-Hagemes, M., Stefan, A., Rissler, J., Gross, Benno, et al., 2018. Monitors vs. Smart glasses: a study on cognitive workload of digital information systems on forklift trucks. In: International Conference On Digital Human Modeling And Applications In Health, Safety, Ergonomics And Risk Management. Springer, Las Vegas, pp. 569–578.

Günthner, W.A., Blomeyer, N., Reif, R., Schedlbauer, M., 2009. Pick-by-vision: Augmented Reality Supported Order Picking. Research Report Technische Universität München.

Hart, S., Staveland, Lowell E., 1988. Development of NASA-TLX (task load Index): results of empirical and theoretical research. In: Hancock, Peter A., Meshkati, Najmedin (Eds.), Advances in Psychology, vol. 52. North-Holland, ISBN 9780444703880, pp. 139–183. https://doi.org/10.1016/S0166-4115(08)62386-9, 0166–4115.

Karrer-Gauß, Katja, Glaser, Charlotte, Clemens, Caroline, Bruder, Carmen, 2009. Technikaffinität erfassen – der Fragebogen TA-EG, vol. 29. ZMMS Spektrum.

Kim, S., Nussbaum, M., Gabbard, J., 2019. Influences of augmented reality head-worn display type and user interface design in performance and usability in simulated warehouse order picking. Appl. Ergon. 74, 186–193. https://doi.org/10.1016/j.apergo.2018.08.026.

Koelle, M., El Ali, A., Cobus, V., Heuten, W., Boll, S., 2017. All about acceptability?: identifying factors for the adoption of data glasses. In: Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems. ACM, Denver, pp. 295–300. https://doi.org/10.1109/ACCESS.2018.2831081 (pp. 28712–28732).

Kolla, Sri Sudha Vijay Keshav, Sanchez, Andre, Plapper, Peter, 2021. Comparing effectiveness of paper based and augmented reality instructions for manual assembly and training tasks (june 4, 2021). In: Proceedings of the Conference on Learning Factories (CLF). https://doi.org/10.2139/ssrn.3859970. Available at SSRN: https://ssrn.com/abstract=3859970.

Rauschnabel, P., Ro, Y., 2016. Augmented reality smart glasses: an investigation of technology acceptance drivers. Int. J. Technol. Market. 11 (2), 123–148.

Rejeb, Abderahman, Keogh, John G., Leong, G. Keong, Treiblmaier, Horst, 2021. Potentials and challenges of augmented reality smart glasses in logistics and supply chain management: a systematic literature review. Int. J. Prod. Res. https://doi.org/10.1080/00207543.2021.1876942.

Rodriguez, F.S., Saleem, K., Spilski, J., Lachmann, T., 2021 Jul. Performance differences between instructions on paper vs. digital glasses for a simple assembly task. Appl. Ergon. 94, 103423. https://doi.org/10.1016/j.apergo.2021.103423, 5, Epub 2021 Apr 8. PMID: 3383952.

Schuster, F., Engelmann, B., Sponholz, U., Schmitt, J., 2021. Human acceptance evaluation of AR-assisted assembly scenarios. J. Manuf. Syst. 61, 660–672. https://doi.org/10.1016/j.jmsy.2020.12.012. https://www.sciencedirect.com/science/article/pii/S0278612520302260, 0278–6125.

Sedighi, A., Ulman, S.M., Nussbaum, M.A., 2018. Information presentation through a head-worn display ("smart glasses") has a smaller influence on the temporal structure of gait variability during dual-task gait compared to handheld displays (paper-based system and smartphone). PLoS One 13 (4), e0195106. https://doi.org/10.1371/journal.pone.0195106.

Smith, E., Reuben, F., Burch, V., Lesley Strawderman, Chander, Harish, Smith, Brian K., 2021. A comfort analysis of using smart glasses during "picking" and "putting" tasks. Int. J. Ind. Ergon. 83, 103133 https://doi.org/10.1016/j.ergon.2021.103133. https://www.sciencedirect.com/science/article/pii/S0169814121000512, 0169–8141.

Terhoeven, J., Schiefelbein, F., Wischniewski, S., 2018. User expectations on smart glasses as work assistance in electronics manufacturing. Procedia CIRP 72, 1028–1032. https://doi.org/10.1016/j.procir.2018.03.060.

Wille, M., 2016. Head-Mounted Displays - Conditions of Safe and Stress-Optimal Use: Psychological Stress during the Use of HMDs, first ed. Federal Institute for Occupational Safety and Health, Dortmund, ISBN 978-3-88261-163-2. project number: F 2288.

Wille, M., Grauel, B., Adolph, L., 2014. Strain caused by head-mounted displays. In: de Waard, D. (Ed.), Proceedings of the Human Factors and Ergonomics Society Europe 2013, pp. 267–277.