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Comparing Augmented Reality Visualization Methods for Assembly Procedures

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Abstract Assembly processes require now more than ever a systematic way to improve efficiency to comply with increasing product demand. Several industrial scenarios have been using Augmented Reality (AR) to enhance environments with different types of information to influence the overall user satisfaction and performance. The purpose of this work is to evaluate three different AR-based methods that can be used to support users during the execution of an assembly process. The AR methods evaluated are hand-held mobile AR, indirect AR (showing the augmented scene on a monitor) and a see-through Head Mounted Display. A user study was performed to assess performance, mental and physical workload and acceptance of the three methods. The study that involved thirty participants did not reveal a best method in terms of performance and user preference, showing that all methods are adequate to support users. However, the study highlights the strengths and weaknesses of each method which may lead to potential advantages for them in specific use cases.

Keywords Augmented reality · User study · Mobile Augmented Reality · Head Mounted Display · Indirect Augmented Reality · Computer-aided manufacturing

1 Introduction

Product assembly is responsible for a large portion of material, resources, time, and cost in the manufacturing of engineered products [1, 2, 3]. While many assembly processes are automated, a significant number of assembly operations still require manual intervention due to their complexity [4]. Conventional assembly processes often resort to descriptive instructions on paper or in digital format (photos or diagrams) to guide the assembly sequence. These traditional methods require technicians to perform the mapping between the instructions and the actions on real objects without any feedback or help [5].

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Through Augmented Reality (AR), it is possible to display digital information (such as step-by-step instructions, 3D illustrations, or other relevant data) directly in the field of view of the users while performing an assembly procedure [6, 4]. This technology may reduce significantly costs for assembly operations through an increase in spatial perception and a reduction in errors, time, and cognitive workload as shown in previous studies [7, 8, 4, 9, 10, 11].

As hardware and software capabilities evolve, more opportunities and challenges arise in the AR ecosystem. In this context, different methods and technological setups have been studied: handheld displays, such as smartphones and tablets are commonly used [12, 13, 14] due to their availability and low price, along with the integration of many multipurpose sensors. Although presenting some limitations[15, 16], custom-built or commercial Head Mounted Displays (HMDs) are also a good alternative for hands-free procedures. Spatial Augmented Reality (SAR) is also capable of provide hands-free operations, but it generally requires more expensive hardware in order to project virtual instructions [17]. With SAR, it is possible to project 3D instructions using this method, equipment like a stereoscopic projector together with shutter glasses are needed increasing significantly the system cost, preventing the execution of some collaborative scenarios [18]. However, there is no clear technological solution for AR use in assembly procedures that stands out. This happen due to several limitations of existing methods, namely comfort, interaction, price and others.

The objective of this work is to compare three AR-based methods, including mobile AR, AR using a camera in a fixed top down view together with a monitor and optical see-through AR HMD. A user study was performed to evaluate performance, ease of use and acceptance of all three different AR configurations in assembly scenarios. The paper briefly presents related works, describes the experimental setup and design, presents and discusses the obtained results, and finally draws some conclusions and ideas for future work.

2 Augmented reality in Assembly Guidance

Several works have already compared different AR methods to assist assembly procedures [19]. Tang et al. [20] performed an experiment to evaluate the use of an optical see-through HMD based AR instructions, in a study with 75 participants using LEGO Duplo blocks. Participants were required to complete LEGO assembly tasks following the instructions presented in different media: 1- Printed media, 2- Instructions on a monitor, 3- Instructions on a see-through HMD, 4- Spatially registered AR instructions on a see-through HMD. The study provided evidence that AR-based systems can improve task performance (lowest average time and number of errors) and reduce mental workload on assembly tasks compared to other media.

Khuong et al. [4] described an AR-based system using the combination of a Head Mounted Display (HMD) and a Kinect sensor to display guidance and error detection information. A preliminary study was conducted with 24 participants using LEGO building blocks. Results showed participants preferred a visualization next to real objects in comparison to the direct overlay.

Buttner et al. [21] presented an in-depth analysis comparing three presentation technologies: HMDs, projection, and baseline paper instructions. Based on the results of an user study with 13 participants, they concluded that the use of projection-based

AR to assist users in assembly processes, instead of HMDs, was the best method. They argued that common HMDs are not very robust under bright light conditions and they limit significantly the users' field of view. Besides performing this analysis, the authors also proposed an approach towards assessing the AR research space with an interactive tool which supports researchers by providing an overview of this design space in the manufacturing field [22].

Funk et al. [9] compared spatially unregistered HMD instructions, tablet instructions, paper instructions and in-situ projected instructions using a Lego Duplo assembly task. The results show that assembling parts is significantly faster using in-situ projection and locating assembly positions is significantly slower using HMDs. In this study, 16 participants also made less errors and have less perceived cognitive load using in-situ instructions compared to HMD instructions. In a follow-up study, an eleven day experiment where each participant assembled different products during at least three full workdays using in-situ projected instructions was performed. Users were divided into two groups: experts and untrained workers. Results showed a decrease in performance for the experts while the system leverages a successful learning for the second group [23].

Loch et al. [24] evaluated an AR-based assistance system integrated in a workstation using a monitor to display instructions and a camera to track the user's workflow and follow the assembly tasks stage automatically. A study was conducted with 17 students using LEGO building blocks. The system was compared with a video-based assistance system. Results showed improvements in accuracy, task performance and reduction in the number of errors and task time when AR was used.

Bosch et al. [10] compared projection versus screen instructions and the impact on productivity, quality and workload in a simulated assembly task. The study showed that projected instructions lead to significantly higher productivity and quality rates compared to instructions presented on a screen. Associated to these higher levels of performance a decrease in the workload of the operator was also noticed.

Blattgerste et al. [25] compared four different AR-based methods using mobile devices, optical see-through HMDs (Microsoft HoloLens and Epson Moverio BT-200) and paper printed instructions. The assembly instructions were provided in two groups: in-situ and in-view (paper instructions in user field of view). Mobile devices and Microsoft HoloLens leveraged the in-situ techniques while the Epson Moverio BT-200 and paper instructions used the in-view approach. In this study, 24 participants solved the Lego assembly task faster using paper instructions, but made less errors with AR assistance on the Microsoft HoloLens than with any other system.

Alves et al. [26] also proposed two different in-situ AR-based (mobile and projection - spatial AR) methods with real-time validation to provide assistance to users during the execution of an assembly process. Results from a user study with 15 participants showed that participants were significantly faster and made fewer errors using the Spatial AR condition being this condition preferred by the majority of the users as well.

An overview of the representative works above mentioned regarding AR Visualizations for assembly can be found in Table 1. Works are presented in rows using first author's last name and sorted chronologically. The columns corresponds to the different visualization methods considered in the study (asterisks indicate the methods considered in a given study while green checkmarks represent the best solution according to the study).

Table 1: Overview of Representative Works in Visualizations methods used to guide assembly procedures - Asterisks indicate the methods used in each study and the green checkmark represents the best method according to the authors.

Visualization method / Authors	Paper instructions	Monitor Display		Spatially Unregistered See-through HMD	Spatially Registered See-through HMD		Mobile AR	Spatial AR	Panel Projection
		Video-based	AR-based		Direct Object Overlay	Near Object Overlay			
Tang et al.	*	*		*	✓				
Khuong et al.					*	✓			
Buttner et al.		*		*					✓
Loch et al.		*	✓						
Funk et al.	*	*		*				✓	
Bosch et al.		*						✓	
Blattgerste et al.	*			*	✓				
Alves et al.							*	✓	

As illustrated in Table 1, Spatially Registered See-through HMD and Spatial AR conditions present the best results overall. However, AR-based Monitor Display is still an unexplored method when compared with the previous methods and may have advantages not yet discovered. For this reason, there is an opportunity to explore how different types of visualization methods are used aiming to better understand the inherent advantages and disadvantages of each one of them.

Although being one of the methods with best results overall, Spatial AR was not considered in this study due to the lack of equipment capable of providing useful 3D instructions as most of projectors are only suitable to present instructions on a flat surface [26, 18].

3 Setup and methods

This section presents the setup and method for a user study using different methods to guide users through an assembly task.

3.1 Experimental Setup

To show the assembly steps to users, we used three methods/set-ups: a mobile device, a AR indirect projection in a monitor and an optical see-through HMD. The perspective in which the assembly instructions are shown are similar in two methods (mobile device and HMD), but different from the monitor display method as it presents the assembly steps using a top down bird's eye view.

3.1.1 Mobile Augmented Reality

The first method uses a mobile device to augment the environment (overlay computer generated information on top of the real world) with the virtual instruction to be assembled in its target pose as shown in Figure 1. We used a natural marker/image to determine the pose of the mobile device, rendering the objects at the correct location. In this method, the user can move the mobile device freely and visualize the assembly under different perspectives. The user controls the assembly step by pressing one of two arrows presented in the screen (right one to advance and left one to go back).

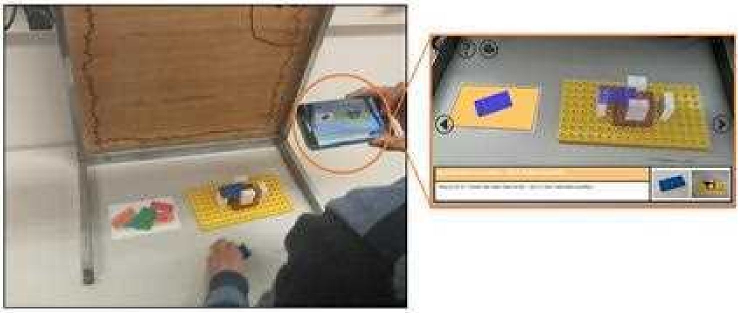

Fig. 1: Method 1 - Mobile Augmented Reality. Use of a mobile device to show the virtual instructions

3.1.2 Indirect Augmented Reality

The second method uses a specific set up, in which a camera is mounted on a stand, pointing towards the surface where the assembly takes place. The setup also includes a monitor to display the assembly instructions as virtual pieces (Figure 2). This method augments the environment by overlaying the instructions on top of the video stream produced by the camera and showing them on a monitor that can be seen by the user while performing the assembly task. The information presented is similar to the one used in the first set-up, with the advantage that the user has his hands free. The only difference is the use of the keyboard right or left key arrows to indicate the assembly guiding system to proceed to the next instruction or return to the previous one. In Section 2, we referred to this method as AR-based monitor display. In the rest of the paper we will use the term Indirect Augmented Reality.

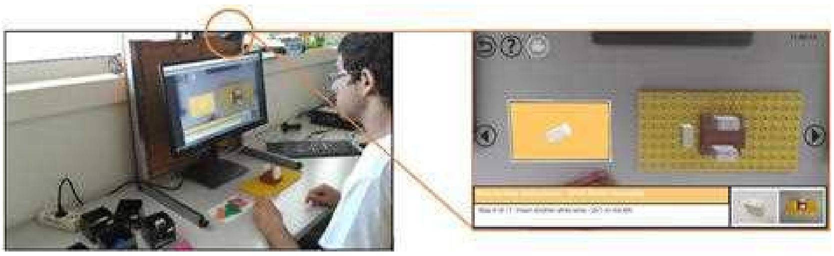

Fig. 2: Method 2 - Indirect Augmented Reality using a top down view. Setup using a camera orthogonal to the assembly and a monitor to display the virtual instructions

3.1.3 Augmented Reality using optical See-Through HMD

The third method uses instructions presented via a see-through Meta 2 HMD to overlay virtual information directly into the users' field of View as show in Figure 3. In this method, a digital counterpart of the table in front of the user is recreated using a 3D reconstruction algorithm, to enable the assembly instructions to be placed on top of the real table. After this process, the user can move the virtual assembly as long as they are on top of the physical table. As in the Indirect AR method, the user controls the assembly step by pressing the keyboard right or left key arrows to proceed to the next instruction or return to the previous one.

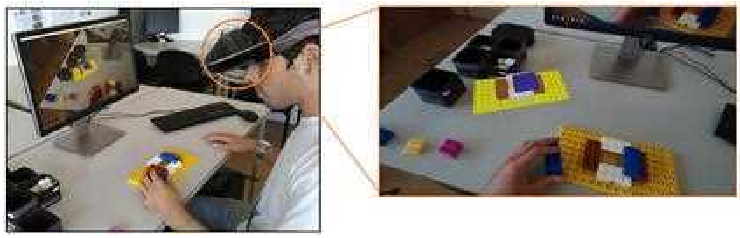

Fig. 3: Method 3 - Augmented Reality using optical See-Through HMD. Use of a HMD to present the virtual instructions directly into the users' vision

The first method (Mobile Augmented Reality) was considered to be one of the methods present in this study because it is currently the most ubiquitous AR method. The second one (Indirect Augmented Reality) was used because it is an unexplored method as mentioned in section 2. In this method we opt for using a top down view because it is the most common setup in industrial settings. The third one (Augmented Reality using optical See-Through HMD) is one of the methods presented that achieved the best results overall in previous studies.

3.2 Experimental Design

A within-group experimental design was used. The null hypothesis (H0) considered was that the three AR-based methods described are equally usable and acceptable to construct a predefined brick assembly.

The independent variable was the information display method provided to the users, with three levels corresponding to the experimental conditions. Before using each condition, an illustrative video was presented to the users showing how to perform the task using the specific AR method. The dependent variables were task performance, perceived mental workload, and participants' opinion. The order in which the methods were used, as well as users' demographic data and previous experience with AR and assembly were registered as secondary variables. To minimize learning effects during the experiment, the users were split into six groups and each group performed the three conditions in different orders.

3.3 Task

The participants were required to complete the assembly of 18 building blocks (grouped into 8 sets as depicted in Figure 4) in 18 step-by step 3 dimensional procedural building instructions, using all the experimental conditions. Each participant built three assemblies as depicted in Figures 5,6,7, one for each method, each representing a generic assembly process. During each step, users were required to place the piece in a pre-defined position (in a specific location and orientation) regarding a predefined base, after the selection a specific size and color piece from the groups available on the workbench. For each experimental condition users had to complete a different block assembly, with the same pieces ordered in different ways to achieve a similar complexity. Previous work [4] showes that users performed better while having the virtual assembly near the real assembly and not superimposed on it. In this study we decided to let participants choose how to build the assembly either by superimposing the virtual pieces on the real assembly or by keeping them apart.

Fig. 4: Assembly Lego Pieces divided in eight groups.

Fig. 5: Task 1.

Fig. 6: Task 2.

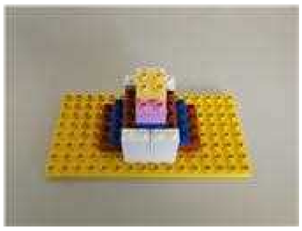

Fig. 7: Task 3.

3.4 Experimental procedure and participants

As mentioned, three types of measures were taken: task performance, perceived mental workload and participants' opinion. Task performance is defined based on the

Table 2: Post-task Questionnaire for evaluating the performance and ease of use of the three methods.

#	Question	Response Type
Q1	Was the amount of information displayed appropriate?	Likert Scale (1:Very Low; 7:Very High)
Q2	Were the assembly instructions difficult to understand?	Likert Scale (1:Very Low; 7:Very High)
Q3	Order the methods according to preference.	Sorted List
Q4	What were the main difficulties?	Open Answer
Q5	After the experiment, I had symptoms of...	Open answer
Q6	Add suggestions you consider relevant	Open Answer
Q7	Add additional comments you may consider relevant.	Open Answer

time of completion (logged by the device, measured in seconds), number of errors and number of corrected errors. Time of completion is the time taken to complete all procedures with each condition. The number of errors measures the number of incorrect actions performed by the participants during each task, where an error can be defined as: E1- a piece with the wrong color is inserted; E2- a piece is inserted at the wrong location; E3-a piece with the wrong shape is inserted. These errors as well as the number of errors corrected by the participants were logged by an observer. The mental workload perceived by the participants during the experiment was assessed using six questions regarding 6 categories as in the Raw Task Load Index (RTLX): mental demand, physical demand, temporal demand, effort, performance, frustration level [27]. These questions were answered using a 10 level Likert-type scale. A post task questionnaire (based on the work by [4, 28, 29]), collected demographic information (age, gender, previous experience with LEGO, AR, and AR in assembly tasks), and participants' opinion concerning the ease of use of each condition, as well as preferences (Table 2). As mentioned, all participants used the 3 experimental conditions, but the order was varied among participants to avoid bias due to learning effects. At the beginning of the experiment, participants were instructed about the experimental setup and tasks, and gave their informed consent. Then, they were asked to consider two levels of priorities: perform the task as accurately and as fast as possible. Afterwards, participants completed the assembly task and were observed by an experimenter who assisted them if they asked for help and used a standard observation form to make annotations (e.g. the number and type of errors, etc.). Immediately after completing the task using the three methods, participants answered the post-task questionnaire. Thirty participants (10 female) aged from 19 to 51 years old (median 26), performed the assembly tasks and completed the post-experience questionnaire afterwards. Participants had various professions (e.g. Master and PhD students from distinct areas, university researchers, and teachers); 21 participants had previous experience with Augmented Reality and nineteen had never used any AR assembly support system.

4 Results

This section presents the main results obtained analyzing the collected data using Exploratory Data Analysis (EDA) [30], ANOVA [31], non-parametric tests [32] and Multivariate Analysis [33].

4.1 Task performance

Figure 8 shows the boxplots concerning completion times with the three methods, Mobile AR, Indirect AR and HMD-based AR, after removing two outliers. The average times for the three methods are 194.5s, 134.8s and 139.9s, respectively. A repeated measures (aka within-subjects) ANOVA was used to compare these average times since the applicability conditions normality and homocedascity were met. Normality was confirmed using a Shapiro-Wilk test and homocedascity through a Levine test. The mean times for the three methods are significantly different: F(2,82)=13.397, p-value=0.0001. Partial Eta squared=0.246 representing a large effect (i.e. confidence in the statistical result), and an observed test power of 0.997. This shows that there are differences among the methods, yet does not specify which pairs of conditions have significantly different average times. Thus multiple comparisons or post-hoc (Tukey, Bonferroni and Sidak) tests were performed. The results showed that there are significant differences between the first (Mobile) and second (Indirect) methods (p-value=0.000) as well as between the first and the third methods (p-value=0.000). However, between the second and third methods no significant difference was found (p-value<0.9).

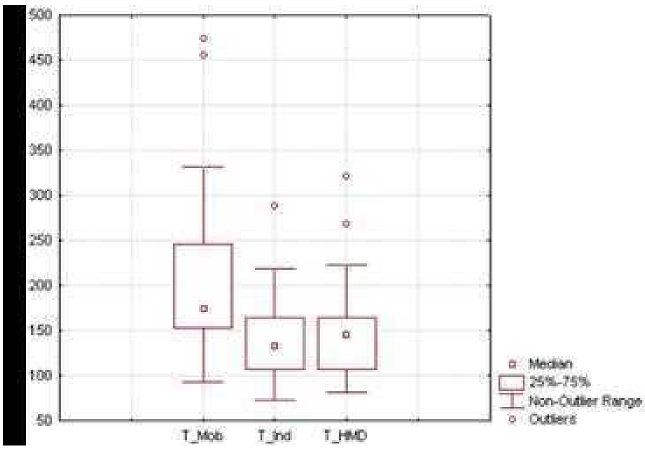

Fig. 8: Task performance from the three methods based on time of completion

The number of errors that participants made with the three methods was also analyzed: 8 with Indirect AR, 22 errors with HMD-based AR and 24 with mobile AR. These numbers suggest that participants using the second (Indirect) method are less prone to make errors. Furthermore, we studied if there was an association between methods and different type of errors (E1- wrong color; E2- wrong location; E3- wrong shape). A contingency table (table 3) and a Fisher-Freeman-Alton's exact (two-sided) test were used, showing that the equality of proportions hypothesis was rejected (p-value=0,0000). Thus, there is an association between the methods and type of errors. A Correspondence Analysis (figure 9), shows that color is not associated with any specific method but location errors are not associated with the second method, but are associated with the first and the third ones. Regarding shape, the first and second methods are more associated with this error type than the third one. These results suggest that participants made less errors regarding the Lego brick shape while using the HMD method.

Table 3: Summary of errors for all methods. Mob: Mobile Augmented Reality; Ind: Indirect Augmented Reality; HMD: Augmented Reality using optical See-Through HMD. Error types: E_color: a piece with the wrong color is inserted, E_Location: a piece is inserted at the wrong location or E_shape: a piece is inserted with the wrong shape. Each type refers to the total number of errors made in each condition.

Condition	Errors		
	E_Color	E_Location	E_shape
Mob	0	9	15
Ind	0	1	7
HMD	3	16	3

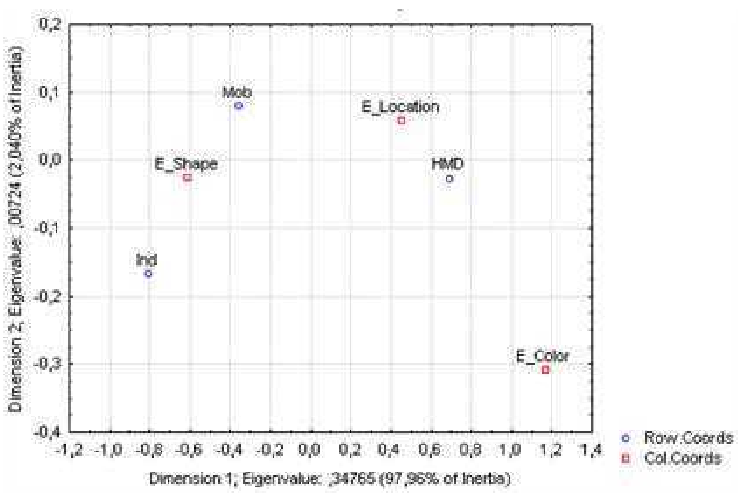

Fig. 9: Association among the methods and types of errors

4.2 Mental workload

The mental workload perceived by the participants during the experiment was measured concerning the six dimensions of the Raw Task Load Index (R TLX): mental demand, physical demand, temporal demand, effort, performance, and frustration level; each corresponding to a question answered with a 10-point Likert-type scale. The results concerning each dimension were compared among the three methods, Mobile AR, Indirect AR and HMD-based AR. As all the participants performed the task using the three methods (within subjects), and the data is on an ordinal scale, the equality of medians was tested with a non-parametric, Friedman test (ANOVA non-parametric test). The results concerning mental and physical demand - dimensions where there is significant differences - between the three methods are summarized in Table 4. Regarding mental demand, the Friedman test rejected the null hypothesis (equality of medians) by a small margin (p-value=0.044), indicating differences among methods; in pairwise comparisons significant differences (α=0.1) were found between Mobile AR and Indirect AR (p-value=0.071), as well as between Indirect AR and HMD-based AR (p-value=0.093). Between Mobile AR and HMD-based AR no significant difference was found (p-value=0.897). Figure 10 shows the boxplots concerning physical demand perceived by the participants with the three methods. The median values are 2, 1 and 2, respectively and the Friedman test rejected the null hypothesis (p-value=0.002). Similarly to the previous case, pairwise comparisons found significant differences (α=0.05) between Mobile AR and Indirect AR (p-value=0.004), as well as between Indirect AR and HMD-based AR (p-value=0.033). Between Mobile AR and HMD-based AR no significant difference was found (p-value=0.439). Concerning the three remaining dimensions of mental workload (temporal demand, performance and effort), the Friedman test accepted the null hypothesis showing no differences among the three methods.

Table 4: Mental and physical demand differences between methods. Filled tabled entries indicate when two methods are significantly different, where the $>$ and $<$ symbols indicate if a method is more or less demanding respectively

Methods	Mobile AR	Indirect AR	HMD AR
Mobile AR		$>$	
Indirect AR	$<$		$<$
HMD AR		$>$	

Another comparison among the methods was performed based on a Cluster Analysis based on the similarity of the answers given by the users concerning each dimension. A hierarchical clustering method (Ward) was used and Figures 11, 12 and 13 show the dendrograms corresponding to the three methods. Observing the figures, it is possible to notice that performance and temporal demand are the most different dimensions and mental demand and effort are closely associated in all methods (red arrows). Moreover, in Indirect AR and HMD-based AR frustration level and physical demand are tightly grouped together. Finally, these two dimensions are associated with frustration level and physical demand in all methods (blue arrows).

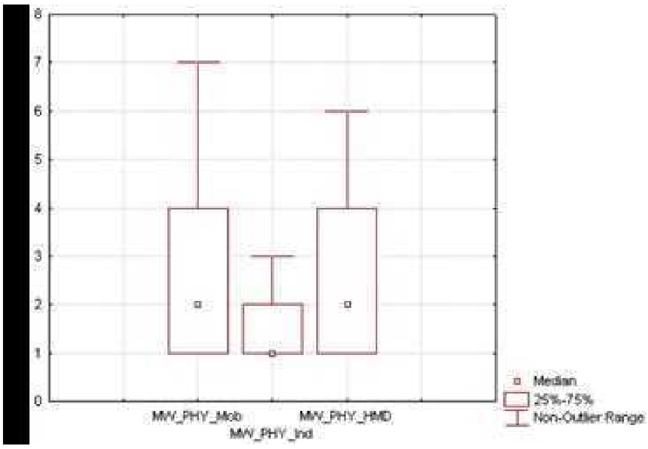

Fig. 10: Boxplots regarding physical demand from the three methods perceived by the participants

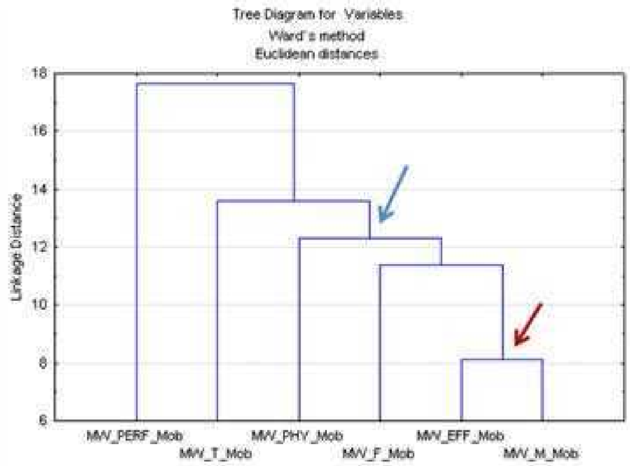

Fig. 11: Mobile AR - Dendrogram of the perceived Mental Workload six dimensions: performance, effort, frustration level and mental, physical and temporal demand

4.3 Users opinions and preferences

Participants answered the post-questionnaire and gave their opinion concerning the three methods, as well as their preferences. The most preferred methods were method 2- Indirect AR, and 3- HMD-based AR, by fourteen and thirteen participants respectively. The amount of information displayed was considered appropriate (median=6.5) and the assembly instructions were considered not difficult to understand (median=2), both in a 7 level Likert type scale with a maximum of 7.

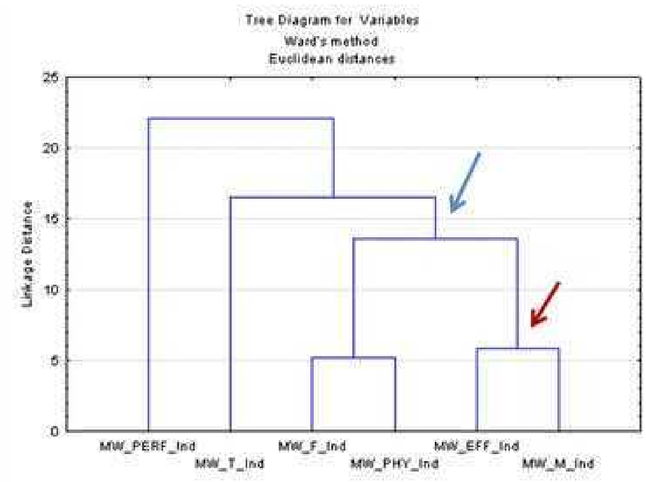

Fig. 12: Indirect AR - Dendrogram of the perceived Mental Workload six dimensions: performance, effort, frustration level and mental, physical and temporal demand

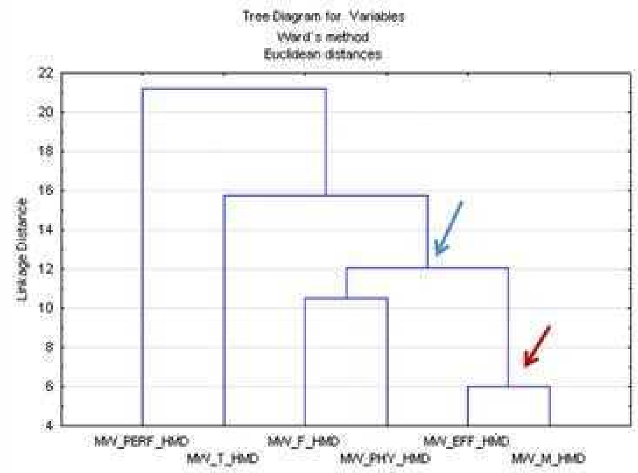

Fig. 13: AR with optical see-Through HMD - Dendrogram of the perceived Mental Workload six dimensions: performance, effort, frustration level and mental,physical and temporal demand

5 Discussion

The most noticeable difference between the three methods was the type of errors performed by the participants. For example, position is not associated with the second method (Indirect AR), but it is associated with the first (Mobile AR) and the third one (HMD). This can be explained because Indirect AR do not force the participants to switch their attention from the instructions to the assembly, as they could perform the assembly step with continuous feedback about their actions. Although HMD also presents this feature, it has alignment problems between the real pieces and the virtual ones due to the headset tracking limitations. Regarding shape, mobile and Indirect AR methods are more prone to propel this type of error than the HMD one. This can be explained by the fact that perspective changes of the assembly are easier to be performed in the third method than in the remaining ones. Regarding errors in the colors, we were anticipating some problems with the Meta 2 Headset. This is due to the fact that even if the HMD is worn correctly by the user, the virtual object might not be as visible as expected, particularly regarding the virtual objects transparency, but this did no result in any significant increase in color errors with the HMD condition. Given this relationship between methods and errors and leveraging the advantages provided by each method, it seems possible to anticipate which might be the best method in different use cases.

Another interesting observation was the fact that most of the participants did not explore the possible advantages provided by some of the methods in the designed tasks, given the freedom to manipulate the initial setup. For example, in the Indirect method participants did not move and/or rotate the marker to get a better perspective of the assembly. In the mobile method, everyone choose to hold the device and not put it down to use both hands in the assembly. In the HMD method, most of the users (20 out of 30) misaligned the real assembly and the virtual assembly in the beginning of the experiment, while one user performed this misalignment only during its course.

This experiment suggests that Mobile AR, a method that may beforehand seems the least adequate method to be used in these assembly scenarios for simple tasks have similar performance with a more flexible and less expensive setup. For example, the differences between it and the HMD-based method are not significant regarding the number of errors. One possible explanation may come from the fact that the HMD used (Meta 2) has tracking problems resulting frequently in misalignment between virtual and real world objects. Even with this problem, the second method in the majority of the aspects tested do not revealed to be significantly superior to the HMD method.

Although the preferences regarding the methods were divided between the Indirect and HMD AR methods, some participants revealed that their preference was influenced by the fact that the HMD used was heavy making it unsuitable to be used during long periods of time. Besides this, the HMD must be tethered to a computational system to perform tracking of its position increasing the cost of using this method. Regarding cost the second method when compared with the last one is less expensive, being possible to replicate it more easily.

As shown by this study, Mobile AR is still a viable method to guide the users through an assembly, being the cheapest method and not requiring any type of complex setup. However, both the second (Indirect) as well as the third method (HMD) can be improved by replacing the transition trigger between steps by a larger object than a keyboard key or even with an assembly automatic verification procedure. Some experimental design characteristics could also have contributed for this specific outcome.

We realized that although tasks using Lego have been widely used in many studies [34] to mimic real assemblies, its use might not be complex enough in order to clearly differentiate between the three methods. With the evolution of the technology and the increasing interest of AR for assembly, it would be important to use more complex and realistic tasks in order to have a better idea of the possible differences

[35]. In simple tasks, the assembly difficulty is so limited that most of the participants independently of the used method performed at a reasonable level making it difficult to fully understand the benefits of one method over another. Industrial scenarios are different among them and may vary in several aspects like noise intensity, illumination, presence of other people, movement, and others, that may difficult the task. Although in this study Indirect AR presented the best results overall, if the task requires motion, mobile AR or an HMD with tracking capabilities would be a more suitable approach.

6 Conclusion and Future Work

This paper presents a study using three different AR-based methods (mobile AR, Indirect AR and HMD AR). Participants had to perform a similar assembly (Lego assembly) task in all conditions and the following variables were evaluated: time efficiency, mental and physical workload and the number of errors performed by the participants while using each of the methods.

Using the Indirect AR method, participants obtained better results in dimensions regarding physical and mental demand. Regarding preference, 14 participants preferred the Indirect AR and 13 the HMD AR. The mobile AR method was the least preferred among the three methods.

We compared different AR based methods and showed that each one of them can impact the time needed to perform assembly related tasks and decrease the number of errors performed in their execution in different ways.

Despite these differences, all three methods are adequate for the tasks evaluated in this work. Besides the results of the study, each method has its own strengths and weaknesses regarding several factors such as price, comfort, ease of interaction, point of view control making them more or less adequate to different applications.

As future work the inclusion of additional tasks with a higher degree of difficulty would be valuable to better evaluate the differences in a more complex interaction. Changing the type of representative building block type can also be a viable research path, as our study suggests that although Lego have been widely used in many studies to mimic real assemblies, these procedures are very simple when compared with real industrial procedures for example. Adding automatic validation to each method would also be a valuable path as it gives the user immediate feedback about the current assembly stage and may compensate for technical limitations like misalignment between the real and virtual world.

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