Visual Management (VM) and Augmented Reality (AR) for Enhanced Assembly Instructions: A Comparative Study of VM-AR vs. VM-Paper-Based Methods

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Abstract. This study explores the potential of Augmented Reality (AR) technology in revolutionizing assembly worker instructions by addressing the limitations of traditional paper-based methods. A study is developed to compare assembly instructions, integrating AR with Visual Management (VM) principles to improve clarity, efficiency, and spatial comprehension. The research involves the creation of a VM-AR laboratory demonstrator in a learning factory, along with both paper-based and AR-based assembly instructions. The case study is based on the assembly of a simulated simplified control panel developed specifically for the experiment. Controlled user trials are conducted to assess key performance metrics based on time, errors, comprehension, and user experience. The results show that AR-based instructions significantly enhance assembly efficiency, reduce errors, and improve user satisfaction compared to traditional paper instructions. This study highlights the potential of combining AR and VM to streamline complex assembly processes and offer strong support to workers in industrial settings.

Keywords: Augmented Reality, Visual Management, Instructions, Assembly Systems.

1 Introduction and Motivation

In contemporary manufacturing, effective training for assembly workers is crucial for maintaining operational efficiency and product quality. Traditional methods often struggle to provide immersive, interactive learning experiences, especially for complex assembly tasks. In many active industrial environments, it is impractical to halt production lines to train new operators. Today, operator training and preparation of future manufacturing experts require multifaceted approaches that emphasize applied practice [1]. The current manufacturing landscape also faces the dual challenges of a shortage of skilled workers and high turnover, which result in significant downtime and production delays as companies are forced to repeatedly teach new hires basic assembly tasks.

This is an Accepted Manuscript version of the following work: O. Aggrey, L. Gualtieri and P. Dallasega, Visual Management (VM) and Augmented Reality (AR) for Enhanced Assembly Instructions: A Comparative Study of VM-AR vs. VM-Paper-Based Methods, in: Advancing Learning Factories: Enabling Future-Ready Skills (CLF 2025), Lecture Notes in Networks and Systems, vol. 1546, pp. 280-287, 2025, Springer. This version of the manuscript has been accepted for publication, after final editorial and peer review (where applicable) is complete, but is not the Version of Record and does not reflect post-acceptance improvements (such as copyediting or typesetting), or any corrections. The final authenticated version is available online at: http://dx.doi.org/10.1007/978-3-031-98883-7_34. Use of this Accepted Manuscript version is subject to the publisher's Accepted Manuscript terms of use: https://www.springernature.com/gp/open-research/policies/accepted-manuscript-terms

Additionally, as more companies hire non-native speakers, language barriers further complicate training. However, despite these challenges, many modern production systems still rely on complex and often ineffective manuals for assembly, service, and measurement instructions, which fall short of the needs of fast-paced learning environments [2]. Integrating visual management (VM) principles with augmented reality (AR) technology has the potential to enhance user performance and improve training outcomes. VM principles can be effectively combined with AR to create a more engaging and informative training experience [3,4]. The use of visual controls, clear information overlays, and real-time feedback can improve training outcomes by reducing errors and accelerating the learning curve [5]. This article addresses the challenge of improving instructional solutions in contemporary manufacturing by developing and testing a combined AR-VM approach, comparing its effectiveness to traditional paper-based instructions.

2 Methodology

2.1 Design and Development

Following a comprehensive requirements analysis, an iterative design and development approach is employed. This phase focuses on creating both VM-AR and VM-paper-based assembly instructions in line with the Structured Design Methodology (SDM). The SDM emphasizes a cyclical process, Ideate, Prototype, Build, and Analyze, that allows for continuous refinement and enhancement throughout development [6]. While the core principles of SDM align with a waterfall model, offering a structured framework with go/no-go evaluations at each stage, the proposed approach is instead iterative, incorporating feedback at every step. The methodology is detailed as follows:

Ideate: The specific features of the use case are defined using an action research approach [7]. This includes identifying the case for lab testing, such as selecting and refining the product, developing the workspace, and defining the process steps. Instructional needs will be established from both the operator and manufacturing company perspectives.

Prototype: It involves designing instructions for both VM-paper-based and VM-AR formats. For VM-paper-based instructions, the focus is on presenting information clearly and linking it to VM principles. For VM-AR instructions, the design includes digital content elements like sequential layering, color-coded VM guides, and icons that help direct the user's actions.

Build: Once the prototype for VM-AR instructions is developed in Unity, it is transferred and configured to run on an AR head-mounted display (e.g., Microsoft HoloLens 2). Concurrently, for VM-paper-based instructions, assembly drawings are created using SolidWorks.

Analyze: It involves setting evaluation criteria to compare both VM-AR and VM-paper-based instructions, assessing their effectiveness through qualitative and quantitative measures.

2.2 Use Case Implementation

Product and process. An emulated machine control panel was selected due to its appropriate complexity and scalability for assembly tasks. The assembly process involved eight components, some similar but all distinct, arranged in a specific sequence with a 15-minute completion time, creating a realistic scenario for testing. The assembly components and their sequence are summarized in Fig. 1A.

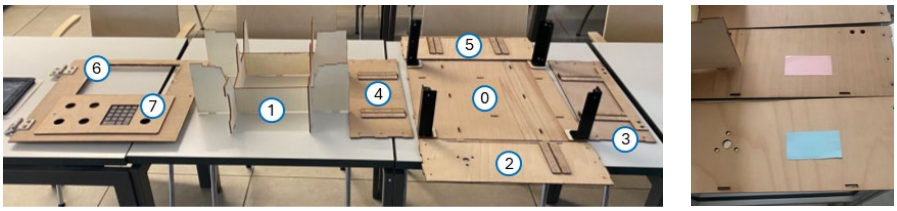


Fig. 1. Emulated machine control panel components and assembly sequence (A) and color-coded sub-assemblies (B).

For the VM paper-based instructions, color-coded assembly drawings were created using SolidWorks to simulate a traditional paper-based manual (enhanced by additional VM aids), while the VM-AR instructions were developed in the Unity environment and provided through the head-mounted display (see Fig. 2). The workspace featured two height-adjustable ergonomic worktables. The task was designed for standing operation, allowing operators to move freely around the assembly station, with the exception of moving the assembly itself. In the picking area, sub-assemblies were marked with simple and highly visible, colored labels on each component (see Fig. 1B) to enhance visual differentiation and streamline the assembly process.



Fig. 2. A comparison of VM-AR (A) and VM-paper-based (B) instructions for the same assembly step.

Digitalization and System Architecture. The digitalization phase translates the physical product and assembly process into digital assets within the Unity environment. The digital models were color-coded to match the colors used in the physical assembly

process, enhancing consistency. Visual guides, such as blue blinking directional arrows, were implemented to provide step-by-step instructions, aligned with VM principles to ensure clear, real-time feedback. Users are guided through each step in a series of seven distinct scenes, each corresponding to a specific assembly step, with seamless navigation facilitated by the "Canvas" class containing navigation scripts. This layout supports focused attention on one task at a time, preventing user overload. The user interface, designed for simplicity, includes "Next" and "Previous" buttons, while clearly displaying the current step and total steps to enhance task progress awareness. In Unity, a 3D table object provides a stable base for the control panel, ensuring precise alignment. The IndicatorScript (from Microsoft MRTK3) and ArrowScript enhance spatial awareness and interaction. Positioned above the control panel, the IndicatorScript guides users to the assembly location by pointing a 3D arrow to the target object, minimizing disorientation. The ArrowScript, positioned below, further promotes engagement through dynamic visual cues, creating a sense of progression that aids learning retention. The Spatial Manipulation Scripts, also from MRTK3, enhance object manipulation by setting environmental bounds. These scripts optimize user interaction, simplifying object transformations like translation, rotation, and scaling. Users can move entire assemblies as cohesive units, rather than individual components, thanks to the box collider mesh that encloses the environment in a cuboid. Users interact with these holographic elements, scaling or manipulating them in real space as needed to support the instructional process.

2.3 Validation

The experimental design involves comparing two groups of participants—one using VM-AR assembly instructions and the other traditional paper-based instructions—with four participants in each group. Participants with prior manual work experience will be selected to ensure familiarity with hands-on tasks. They will be randomly assigned to each group to reduce potential bias. To prepare the VM-AR group, a 10-minute pre-test session will introduce them to the AR technology, while the paper-based group will receive a brief explanation of how the color-coded VM paper instructions align with real-world object colors. This same explanation will be provided to the VM-AR group for consistency. Both groups will complete the same assembly task in a controlled laboratory environment, and the comparison will be based on defined Key Performance Indicators (KPIs), as outlined in the following:

Total Assembly Time (KPI-1) – Measures the overall time taken to complete the assembly, indicating the efficiency of each instructional method.

Instructions Understanding Time (KPI-2) – The time participants take to comprehend each step, assessing instructional clarity.

Understanding to Action Ratio (KPI-3) – Calculated as action time (assembly time minus understanding time) divided by understanding time, where more time on assembly than understanding suggests efficiency in task execution.

Error Correction Time (KPI-4) – Time spent identifying and fixing errors, with zero recorded if an error is promptly corrected.

Net Assembly Time (KPI-5) – Total assembly time minus understanding and error correction time, reflecting actual productive time.

User Experience (KPI-6) – Satisfaction with each instructional method, rated on a 5-point Likert scale from -2 (Very dissatisfied) to +2 (Very satisfied) The final value is the cumulative sum of all rated criteria.

Number and Severity of Errors (KPI-7) – Tracks mistakes during assembly, with minor errors weighted at 0.5 and severe errors at 1.0.

User experience was assessed with pre- and post-test evaluations, while KPIs like time and error rates were gathered from video footage using a checklist.

3 Results

Table 1 provides a summary of key performance indicators (KPIs) comparing VM-AR and VM paper-based methods.

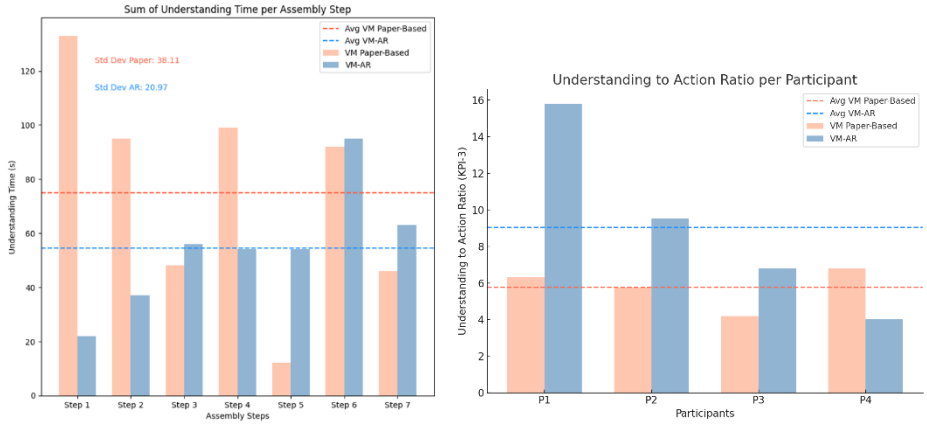
Table 1. Summary of KPI Results.

Participants		KPI-1	KPI-2	KPI-3	KPI-4	KPI-5	KPI-6		KPI-7
							Pre-test	Post-test	
VM-paper-based	P1	14 min, 43 s	2 min, 1 s	6.30	4 min, 49 s	8 min, 15 s	0	-5	3.0
	P2	14 min, 16 s	2 min, 7 s	5.74	0 s	12 min, 9 s	6	-4	3.0
	P3	12 min, 59 s	2 min, 30 s	4.19	0 s	10 min, 9 s	3	3	0.0
	P4	16 min, 31 s	2 min, 7 s	6.80	5 min, 11s	9 min, 34 s	-1	-14	1.5
VM-AR	P1	11 min, 05 s	0 min, 39 s	15.79	0 s	10 min, 16 s	-3	28	0.0
	P2	11 min, 45 s	1 min, 7 s	9.52	0 s	10 min, 38 s	-1	15	0.0
	P3	10 min, 55 s	1 min, 24 s	6.80	0 s	9 min, 31 s	0	8	0.0
	P4	16 min, 1 s	3 min, 11 s	4.03	1 min, 36 s	11 min, 14 s	-2	24	1.5

Each KPI result is discussed below, some with supporting graphs to illustrate key trends and insights:

Total Assembly Time (KPI-1) – Participants guided by VM-AR instructions completed the assembly process faster than those using paper-based instructions. The consistently lower assembly time for AR users underscores the effectiveness of AR in streamlining the assembly processes (see Table 1).

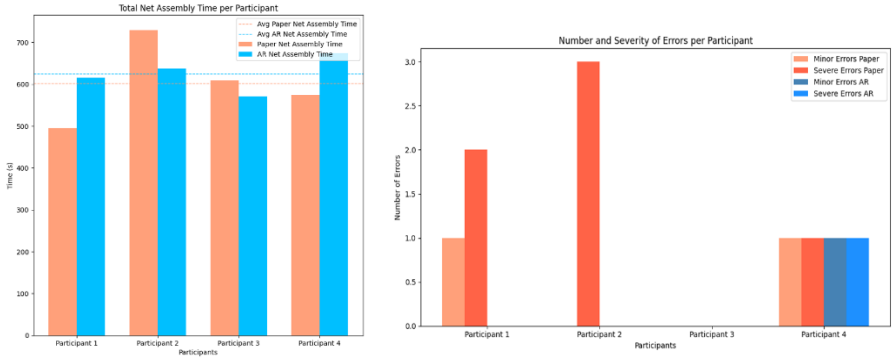
Instructions Understanding Time (KPI-2) and Understanding to Action Ratio (KPI-3) – The mean understanding time for VM paper-based participants (red dashed line) is significantly higher than for VM-AR participants (blue dashed line), indicating that AR-based instructions reduced comprehension time (see Fig 3A). Furthermore, the understanding time variability is higher for VM-paper participants (S. D. = 38.11) than for VM-AR participants (S.D. = 20.97), suggesting more consistent comprehension with AR instructions. On the right (see Fig 3B), VM-AR participants (blue dashed line) showed consistently higher understanding-to-action ratios than VM paper-based participants (red dashed line), highlighting the efficiency of AR-based instructions by allowing more time for assembly than comprehension.



(a) (b)

Fig. 3. Understanding Time per step (a) and Understanding to Action Ratio per participant (b).

Net Assembly Times (KPI-5), Number and Severity of Errors (KPI-7) and Error Correction Time (KPI-4) – VM paper-based participants had lower net assembly times than VM-AR users, though AR's UI interaction added time for AR participants. In contrast, error correction times were significantly higher for paper-based users, who also made more frequent and severe errors (notably Participant 1 and Participant 2). Additionally, VM-AR instructions reduced both error frequency and severity, highlighting AR's effectiveness in minimizing assembly mistakes (see Fig 4).



(a) (b)

Fig. 4. Net Assembly Time (a) and Error Rate (b).

User Experience (KPI-6) – VM paper-based participants showed a decline in post-test cumulative scores, reflecting lower satisfaction and confidence after assembly. This suggests that traditional paper instructions may not fully support users throughout the process, possibly leading to frustration and decreased confidence. Conversely, VM-AR participants displayed significant improvements in post-test cumulative scores (see Fig. 5), underscoring AR's effectiveness in boosting user satisfaction and confidence.

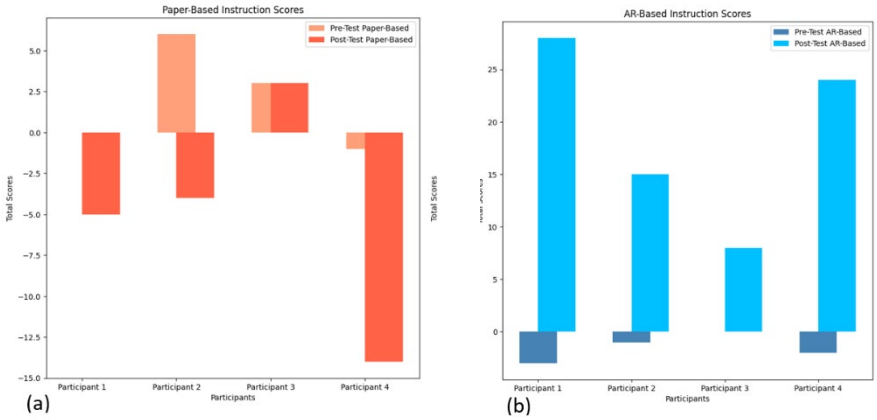


Fig. 5. Pre-Test and Post-Test cumulative scores of VM-Paper (a) and VM-AR (b).

4 Discussion and Conclusions

Results show that AR-based instructions significantly improve the efficiency, consistency, and user experience of the assembly compared to traditional paper instructions. Participants using AR completed the assembly faster, with less variability in performance, indicating that AR offers more intuitive, real-time guidance. Key metrics, like reduced understanding time and higher understanding-to-action ratios, showed that

AR helps users quickly comprehend instructions and focus on the task itself. While AR users spent more time on net assembly due to interactions with the device, they experienced shorter error correction times, suggesting that AR minimizes errors. AR participants reported higher satisfaction and confidence levels, with pre- and post-test results showing substantial gains in perceived ease and satisfaction. These results are particularly valuable in industrial settings where reduced assembly time and fewer errors can significantly lower costs and boost productivity. The consistent performance among AR users suggests that AR can help standardize training outcomes, delivering high precision and uniformity. The success of AR highlights the potential of immersive, interactive learning tools to enhance engagement and motivation in training programs. However, it also points to the need for user-centered design in AR interfaces and related training programs, as some participants experienced delays due to interaction with the UI of the device. This research is limited by a small participant sample, preventing statistical analysis. Future studies should consider a larger sample and incorporate measures, such as longer test durations, to better simulate full shift working conditions and strengthen result robustness.

Acknowledgments. This research is part of the project 'SME 5.0—A Strategic Roadmap Towards the Next Level of Intelligent, Sustainable and Human-Centred SMEs' (funded in the European Union's Horizon MSCA 2021 programme under the Marie Skłodowska-Curie grant agreement No. 10108648).

Disclosure of Interests. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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