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Exploring the Distinctive and Synergistic Affordances of AR and VR for Complex Psychomotor Training

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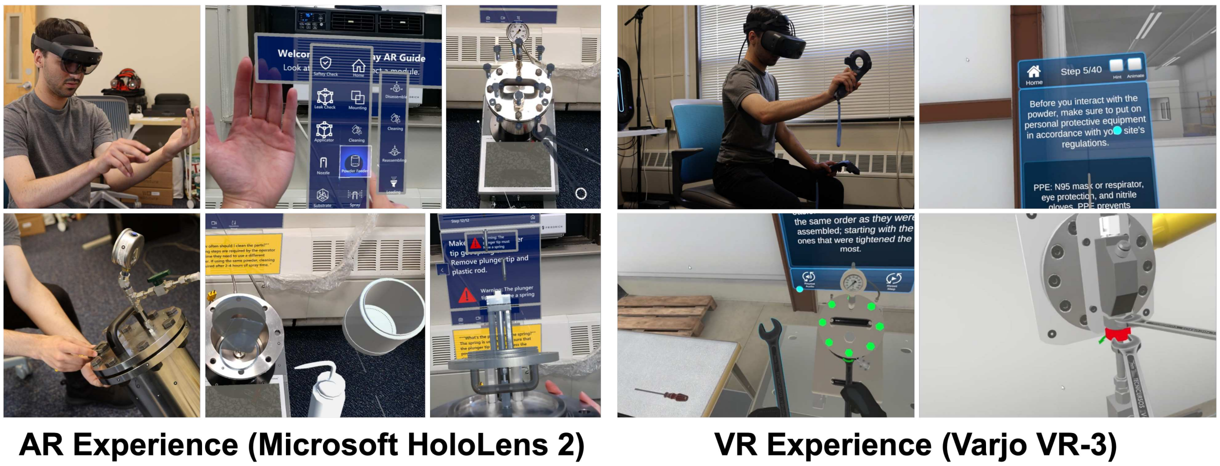

Figure 1: Training experiences using AR and VR for the disassembly and reassembly of a powder feeder [1]. The illustration displays dialogue boxes specific to both AR and VR learning modules. In the AR application, the physical equipment (Powder Feeder) and necessary tools are visible, whereas the VR application utilizes a CAD replica of the equipment.

ABSTRACT

This paper explores the distinctive and synergistic affordances of augmented reality (AR) and virtual reality (VR) for industrial training. The aim is to determine if the combined use of these technologies offers added benefits, and if so, what the preferred deployment order is. Twenty subjects participated in a two-stage study using complementary AR and VR training systems for the disassembly and reassembly of an industrial-grade powder feeder in different sequences to compare key metrics. This unique study design highlights the distinctive benefits of each mode of learning, with VR being favored for safe exploration, and AR providing higher confidence and ease of learning. The findings underscore the synergistic benefits of implementing both AR and VR in the development of training systems for complex psychomotor tasks, with the order of exposure not significantly affecting the learning outcome.

Index Terms: Augmented Reality, Virtual Reality, Industrial Training, Engineering Education, Psychomotor Skills.

1 INTRODUCTION

Industry 4.0 marks a transformative shift in the manufacturing sector, necessitating advanced training methodologies aligned with integrating smart technologies such as automation, IoT, and AI [2]. In this context, AR and VR emerge as essential tools, offering immersive and interactive learning experiences that traditional methods cannot replicate [3, 4]. This paper compares the implementation of AR and VR training systems in an industrial context, specifically mechanical assembly and maintenance. By evaluating the learning outcomes facilitated by AR and VR, we aim to understand which technology better supports knowledge and skill acquisition and if the sequencing of AR and VR exposure impacts learning effectiveness. Previous studies have shown that both VR and AR are effective learning tools when compared to traditional modes of learning[5, 6]. By using our symbiotically designed AR and VR application for learning the assembly and disassembly steps for an industry-grade powder feeder used in cold spray we aim to:

1. Comprehensively analyze the comparative and collective effects of AR and VR on learning complex psychomotor tasks.
2. Understand the preferred order of exposure to AR and VR systems for optimal learning experience and outcomes.

Incorporating findings from studies that discuss the rapid adoption and integration challenges of AR and VR in industrial sectors, this paper will contribute to the development of effective training methodologies. These methodologies will capitalize on the strengths of these technologies, thereby enhancing industrial training while addressing the integration challenges and opportunities identified by previous studies by as described next[7].

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2 RELATED WORK

AR and VR are shown to address some of the limitations of conventional industrial training approaches by offering repeatable, engaging, and immersive learning scenarios [7, 3, 8]. AR provides real-time data overlays that facilitate precise operations, significantly reducing errors and improving task completion times by up to 25%. Additionally, another study indicates that AR interventions can reduce errors by up to 30%. [9, 6]. VR, on the other hand, offers immersive environments that enable trainees to experience

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lifelike scenarios without associated risks, which improves performance in actual operations [3] while other studies have shown that VR training can effectively teach procedures for maintenance tasks [5]. Recent studies highlight that combining AR and VR creates immersive simulations that enhance understanding of complex processes and improve hands-on training efficacy. Integrating these technologies enriches the learning experience and addresses conventional training limitations by providing safe, repeatable, and engaging scenarios. The sequence and modality of exposure are crucial for maximizing learning outcomes [10]. These studies suggest that a thoughtful implementation strategy that considers the order of AR and VR exposure can maximize learning outcomes and operational readiness. However, while existing research highlights the benefits of AR and VR in training, there is a notable lack of studies examining the optimal sequence for their use therefore, further research is needed to explore how the order of implementation can potentially impact training effectiveness and outcome.

Although AR and VR offer significant benefits for industrial training, gaps remain in understanding their optimal sequence and modality for exposure. Studies [4, 8] indicate varied effects on learning curves and retention yet comprehensive data is lacking . There is also a need for comprehensive assessment tools to measure cognitive load, engagement, and knowledge retention [3]. Integrating AR and VR with traditional training methods has yet to be fully explored. Future research should investigate how these technologies can be used both sequentially and concurrently to enhance training environments. Leveraging AR's contextual information and VR's complex simulations could optimize outcomes. Addressing these gaps will improve training programs and theoretical understanding of immersive learning guiding the strategic use of AR and VR in industry [4, 8].

3 Research Question and Metrics

Building on previous research which has shown AR and VR are effective learning techniques this paper aims to understand the distinctive and synergistic affordances of AR and VR as tools for inspection and maintenance, as well as the intricacies of the order of exposure of both these modes of learning. **Research question:** Which skills and concepts are most effectively acquired through the individual and combined utilization of AR and VR, and how does the sequence of exposure impact their acquisition? To answer this question, we examine the following hypotheses: **H1:** AR and VR differ significantly in training completion time. **H2:** Both AR and VR are effective learning tools. **H3:** Learning outcomes differ significantly between AR and VR after the first session. **H4:** Workload experienced by learners differs significantly between AR and VR. **H5:** Perceived usability of AR and VR as training tools differs significantly. **H6:** Perceived confidence gained through AR and VR differs significantly. **H7:** The order of AR and VR exposure significantly influences performance speed and accuracy.

The following metrics were used to measure performance and learning: **Training completion time:** Time (in minutes) needed to complete all training modules. **Knowledge assessment test:** Number of correctly answered knowledge-based questions in each LOQ(Learning Outcomes Questionnaire), tracking changes with six multiple-choice questions. **Number of errors:** Six major errors identified: (a) incorrect step order, (b) incorrect lower wave spring orientation, (c) incorrect upper wave spring orientation, (d) incorrect light seal test execution, (e) incorrect drum lock step execution, (f) incorrect bolt fastening pattern. **Training activity workload:** Reported workload levels, rated 1 to 7, using the NASA-TLX scale [11]. **AR/VR usability:** Usability ratings of Varjo VR-3 and HoloLens 2, on a scale of 1 to 5, incorporating standardized usability questions [12]. **Perceived confidence and effectiveness:** Evaluates how autonomy impacts perceived confidence and effectiveness in using AR/VR tools. [13].

4 Study Design

Participants. Twenty engineering graduate students with a background in mechanical tools participated in this study. A demographic survey was conducted to ensure ethical standards and collecting baseline data on VR and AR familiarity. Participants (17 males, 3 females) were assigned to two groups using stratified randomization: **Group 1** received VR training first with a Varjo-VR3 headset, followed by AR training with a HoloLens 2 (VR → AR), **Group 2** received AR training first with a HoloLens 2, followed by VR training with a Varjo-VR3 (AR → VR). Applications designed for both experiences have been designed to be complementary and source files are publicly available on the website[1]. Adequate time was provided for familiarization with the devices. Participants could withdraw if they experienced discomfort. Group assignment considered familiarity scores (*AR*: 43.56, *VR*: 46.30) to control for biases [14].

Learning Outcome Questionnaire (LOQ). At 5 different stages of the experiment participants' feedback was gathered using a combination of NASA-TLX, the System Usability Scale (SUS), technology-related inquiries, knowledge assessment queries, and open-ended questions to capture their learning experiences comprehensively [12, 11]. Knowledge assessment questions adhered to Bloom's taxonomy to evaluate learning outcomes [15]. Data collection points included four LOQs, as follows.

LOQ0: Pre-experiment consent form and baseline knowledge survey. **LOQ1:** Post-Session 1 questionnaire on learning progress and outcomes, including the same knowledge assessment as LOQ0. **LOQ2:** Post-Session 2 questionnaire comparing learning progress and outcomes, including the same knowledge assessment as LOQ0 and LOQ1. **LOQ3:** One-week follow-up assessment of the powder feeder task and retention questionnaire with the same knowledge assessment questions. **LOQ4:** Post-experiment questionnaire evaluating cognitive load, self-efficacy, and AR/VR experiences through structured and open-ended questions.

Experimental Task. A powder feeder in a cold spray system is crucial for providing a consistent and controlled supply of powder particles into the spray nozzle. It operates by using a rotating drum to transfer powder from a storage tank into a mixing chamber, where it combines with a carrier gas for transport to the nozzle. This system ensures continuous operation without clogging and allows precise control over the powder flow rate [16]. Considering the importance of precise operational and maintenance details, our experiments focus on teaching participants how to accurately disassemble and reassemble the powder feeder.[17].

Disassembly steps: (1) Check pressure gauge; (2) Remove bolts; (3) Open fill port; (4) Remove upper wave spring; (5) Remove drum and metering block; (6) Remove the lower wave spring. **Reassembly steps:** (1) Correctly orient the lower spring; (2) Perform light test; (3) Replace the metering block; (4) Replace and lock drum; (5) Replace upper wave spring; (6) Replace fill port; (7) Fasten bolts in the correct pattern.

5 Results

This section presents the results of the experiment using quantitative and qualitative measures. For all the measured metrics, normality was measured using the Wilcoxon test and as appropriate, Mann-Whitney U Test was used to compare the independent groups.

Training Completion Time. The average time taken for completion of the VR task was 24 minutes for Group 1 (*SD* = 6:46 minutes) and 25 minutes for Group 2 (*SD* = 7:16 minutes). For AR tasks, the time of completion was 18 minutes for Group 1 (*SD* = 7:03 minutes) and 20 minutes for Group 2 (*SD* = 3:40 minutes). Undertaking the Mann-Whitney U Test to understand the difference between the AR and VR we see no statistical significance in time

Table 1: Combined statistical analysis of Mental Workload and Performance for LOQ1 and LOQ2 using Mann-Whitney U Test.

Question	Mean		p-value	Z
	Group 1	Group 2		
Mental workload (LOQ1)	4.0	2.6	0.040	70.0
Mental workload (LOQ2)	3.7	4.2	0.404	34.5
Performance (LOQ1)	4.3	2.6	0.030	71.5
Performance (LOQ2)	3.8	3.8	0.967	46.0

of completion for Group 1 (p = 0.38) and similarly for Group 2 (p = 0.29) as well. Thus we can reject Hypothesis **H1**.

Knowledge Assessment Test. Both groups were exposed to the same sets of questions at various stages of the experiment (i.e., LOQ0–LOQ3). These questions were based on the steps to be performed and there were 6 questions at each stage. Hypotheses **H2** and **H3** were addressed using this metric. As a baseline at LOQ 0 participants, the number of correct responses is 1.36 which increases to 3.68 to LOQ 1 which indicates that both AR and VR are reliable modes of learning (p = 0.000326). Thus we can accept **H2**, showing the effectiveness of both AR and VR in learning the task. Additionally, at LOQ 2, there is a slight increase in test scores for Group 2 (M = 4.1) (AR→VR) compared to Group 1 (M = 3.8) but the difference is not statistically significant (p = 0.32) leading to rejection of Hypothesis **H3**.

Errors in Task Performance. After both learning activities, participants returned after a week to perform all the tasks without any aid. Both groups demonstrated comparable performance, achieving an average of 4 correct steps. Specifically, Group 1 achieved 3.7 correct steps, while Group 2 achieved 4.33 correct steps. Using the Mann-Whitney U test to compare both groups, we obtained a p-value of 0.22, thus rejecting Hypothesis **H7**.

Training Activity Workload. Using standardized metrics such as NASA-TLX helped participants respond to several questions to measure their workload after both the training experience. [11] Given the nature of the task and the specific learning objectives, further analysis focused on raw data from responses to the questions: *Mental demand*: How mentally demanding was the task? *Performance*: How hard did you have to work to accomplish your level of performance? The responses from participants indicate that Hypothesis **H4** is accepted, with a significant difference in mental workload and effort required for learning via AR and VR. This effect is nullified post the second exposure indicating that the methodology of learning plays a key role in activity workload.

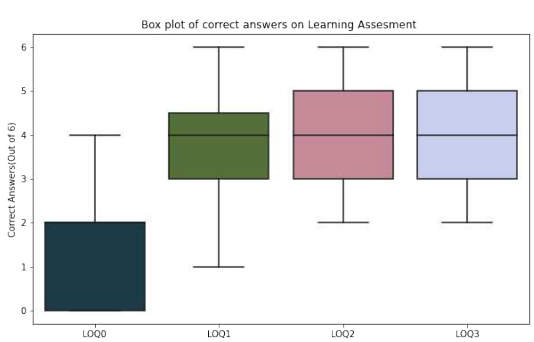

Figure 2: Changes in test scores from LOQ0 to LOQ3.

Perceived AR/VR Usability. We adopted the standardized SUS questionnaire [12] to address Hypothesis **H5**. Breaking down the SUS scale gives us insights into the components and how they differed based on the order of exposure. For the research question we looked at questions related to "I found the various functions in this system were well integrated." which indicated that after the first learning experience, there was a significant difference (p= 0.03). Upon further analysis after both the learning exposures participants found a difference in "I found the system unnecessarily complex." (p = 0.04) which indicates the differences in precipitation using AR and VR systems. Thus, Hypothesis **H5** is accepted.

Perceived AR/VR Confidence and Effectiveness. The same questions, "How confident are you to perform the task on the real powder feeder based on your learning experience?" and "How effectively did the learning experience enhance your hands-on skills in performing the tasks?" were tracked to test Hypothesis **H6**. For Group 1, the average confidence at LOQ1 (M = 3.78, SD = 0.97) was slightly lower than at LOQ2 (M = 4.22, SD = 0.97). Similarly, the average effectiveness of learning skills at LOQ1 (M = 3.67, SD = 0.71) was also lower than at LOQ2 (M = 4.44, SD = 0.53). For Group 2, the average confidence at LOQ1 (M = 4.10, SD = 0.88) was slightly lower than at LOQ2 (M = 4.30, SD = 0.67). Similarly, the effectiveness of learning experience at LOQ1 (M= 4.00, SD = 0.94) remained constant at LOQ2 (M = 4.00, SD = 0.82). Results of a Mann-Whitney U test across the group indicate no significant difference in confidence (p = 0.37) for the 1st question or learning effectiveness (p = 0.49). Thus, we can reject **H6**.

Qualitative Feedback. After each of the two learning sessions, participants were asked to reflect on aspects of the training that either helped or did not help their learning process. Following the second learning experience, participants provided insights on how this session helped fill the gaps left by the first session, enhancing their overall understanding. Below, we discuss the common patterns noticed at each point in the experimental design.

1. *Effectiveness of the first learning experience*: Participants appreciated AR for supporting hands-on training, which allowed them to interact with holographic overlays of components in real-time, making learning intuitive and engaging. VR was praised for its immersive and clear, detailed visual understanding of the assembly processes.
2. *Effectiveness of the second learning experience*: The second exposure reinforced the knowledge gained in the first session. VR continued to be valued for its detailed visualizations, helping clarify further operational procedures and tasks. AR's advantage lay in its continuous provision of a tangible, interactive experience with actual components, which was crucial for building a comprehensive technical understanding.
3. *Limitations of AR and VR*: Challenges with AR focused on user interface issues such as unresponsive buttons and not well-aligned visual aids, which sometimes hindered the learning process. VR criticisms were centered around its inability to replicate the physical interaction with components, which participants felt was essential for a complete learning experience. In VR, participants still found navigating the interface challenging, indicating a need for improved user interaction designs. In AR, although the real-time interaction was beneficial, some participants pointed out issues like the visibility and clarity of instructional overlays.

6 Conclusions

Building on previous research, that often examined AR and VR in isolation, this investigation directly compares their effectiveness across the same tasks, providing a comparative analysis of their applications in training environments[18]. Throughout the experiment, participants noted a significant improvement in their ability to perform tasks and their understanding of the powder feeder. The transition between AR and VR helped participants appreciate different aspects of the learning process: VR for theoretical knowledge and exploration and AR for practical skills. When asked about their preference after the second session, there was a slight favor towards AR due to its direct interaction with the physical parts, which aided in better retention and understanding of the task workflow with the learning outcome for both the groups being comparable.

Summary of Findings. When examining both modes of learning, VR users demonstrated a slight advantage in task completion times compared to AR users which could be due to the VR's singular step-by-step path to completion, which may reduce the time needed for task familiarization and execution. Significant improvements in knowledge assessments were observed across both technologies, affirming their ability to facilitate the understanding of complex tasks. While not significant, data revealed that participants who began with AR experienced better comprehension, possibly due to immediate practical engagement offered by AR, which potentially enhances the retention of knowledge subsequently reinforced through VR's immersive simulations.Based on open responses this insight enabled better comprehension, which could be further investigated.Changes in perceived confidence were noteworthy, with participants who transitioned from VR to AR reporting a more significant increase in confidence. This effect likely results from the direct and interactive nature of AR, which may provide a stronger sense of control and mastery over real-world tasks. Conversely, the transition from AR to VR did not show as distinct a confidence boost, suggesting that once users are accustomed to interacting with real-world elements, the abstract and simulated environment of VR has less of an impact on confidence levels. The initial experiences with each technology revealed significant differences in workload and usability which were significantly reconciled after the participants' second exposure to the technologies, suggesting an adaptation effect. Familiarity with the unique interfaces and interaction styles of AR and VR appeared to reduce cognitive load and streamline task execution during subsequent uses, emphasizing the benefits of mixed-reality training regimens that incorporate repeated exposure to both AR and VR systems.

Limitations and Future Research. The presented study involving twenty engineering students and focused on the specific task of powder feeder assembly and disassembly is limited in terms of generalizability. The participants' background in AR and VR technologies could have influenced the outcomes. To broaden the study's applicability, future research should involve a more diverse group from various professional sectors and with different technical skills. Longitudinal studies are also crucial to evaluate long-term skill retention, ensuring that AR and VR training remains effective and adaptable across modern industries. Additionally, given the knowledge assessment tests had six questions, a possible test with additional knowledge-based questions can be incorporated. While the powder feeder task provides a variety of psychomotor skills to be implemented, additional use cases need to be explored for a more holistic overview of the usage of AR and VR. A mixed study design reviewing multiple tasks can provide insights into knowledge retention and transfer skills enabled by both modalities. This insight can be valuable for learning more about the transfer of skills which is essential in an industrial environment.

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