Field Experiment of Assembly Accuracy with Augmented Reality Overlays in Aircraft Maintenance Training

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Abstract

The integration of augmented reality into industrial training protocols represents a significant paradigm shift in how complex spatial tasks are taught and executed. This study presents comprehensive field experiment evidence assessing the impact of augmented reality overlays on assembly accuracy within the highly critical domain of aircraft maintenance training. As modern aviation systems grow increasingly complex, the cognitive demand placed on maintenance technicians escalates, thereby increasing the risk of assembly errors which could lead to catastrophic failures. Traditional training methodologies, which rely heavily on two-dimensional technical manuals and abstract diagrammatic reasoning, often fail to adequately support the spatial cognition required for three-dimensional assembly tasks. To address this gap, we conducted a rigorous field experiment involving novice technicians tasked with assembling a high-fidelity aircraft hydraulic pump mechanism. Participants were divided into a control group utilizing standard interactive electronic technical manuals and an experimental group utilizing head-mounted augmented reality devices that provided context-aware, three-dimensional holographic overlays. The empirical evidence demonstrates a substantial reduction in both critical and non-critical assembly errors among participants trained with augmented reality overlays. Furthermore, the data suggests that augmented reality significantly mitigates extraneous cognitive load by spatially anchoring instructional information directly onto the physical task space. These findings offer robust empirical validation for the adoption of augmented reality in safety-critical maintenance training, highlighting its potential to enhance assembly accuracy, streamline skill acquisition, and ultimately improve the operational reliability of aviation systems.

Keywords: Augmented Reality; Aircraft Maintenance; Assembly Accuracy; Field Experiment; Computer Vision

1. Introduction

1.1 Problem Statement in Aviation Maintenance

The aviation industry operates under some of the most stringent safety and reliability standards in the global transportation sector. Within this highly regulated environment, the maintenance, repair, and overhaul of aircraft components represent a critical line of defense against catastrophic mechanical failures. The modern commercial aircraft is an exceedingly complex amalgamation of mechanical, hydraulic, and avionic systems, comprising millions of individual parts that must function in perfect harmony. Maintenance technicians are tasked with the formidable responsibility of ensuring these systems are assembled, calibrated, and maintained with absolute precision. However, human error during maintenance operations remains a persistent and significant vulnerability. Research consistently indicates that a substantial proportion of aviation incidents and accidents can be traced back to maintenance-induced anomalies, particularly those involving incorrect assembly procedures, omitted components, or improper torque applications [1].

The primary cognitive bottleneck in traditional aircraft maintenance training and execution is the translation of two-dimensional instructional information into three-dimensional physical actions. Technicians have historically relied on paper-based manuals or, more recently, interactive electronic technical manuals displayed on ruggedized tablets or workstation monitors. These instructional modalities require the user to frequently shift their visual attention between the instructional medium and the physical workpiece, a process known as attention switching. This constant cognitive context switching induces significant extraneous cognitive load, as the technician must mentally construct a three-dimensional spatial representation of the assembly from two-dimensional diagrams, retain that representation in working memory, and subsequently apply it to the physical components before them [2].

In complex assembly tasks, such as the overhaul of a hydraulic power generation unit or the intricate assembly of turbine blade locking mechanisms, the spatial ambiguity inherent in traditional manuals often leads to interpretation errors. A technician might misorient a directional valve, install a sealing ring of the wrong specification, or sequence the assembly steps incorrectly due to a misinterpretation of a complex schematic. These seemingly minor deviations can have profound cascading effects on the structural integrity or functional performance of the aircraft. Consequently, there is an urgent and critical need within the aviation industry to develop and validate novel training methodologies that can mitigate these cognitive bottlenecks, reduce reliance on abstract spatial reasoning, and directly enhance assembly accuracy at the point of action [3].

1.2 Research Objectives and Institutional Context

The advent of head-mounted augmented reality technologies offers a highly promising solution to the spatial and cognitive challenges inherent in aircraft maintenance training. By utilizing advanced spatial computing, augmented reality systems can project context-aware, three-dimensional holographic overlays directly onto the physical components in the real world. This capability effectively eliminates the spatial disconnect between the instructions and the task space, allowing technicians to receive step-by-step guidance that is physically registered to the exact location where the action must be performed. Despite the strong theoretical rationale for the adoption of augmented reality in industrial settings, empirical evidence derived from rigorous field experiments in authentic, safety-critical environments remains sparse. Much of the existing literature relies on highly controlled laboratory studies involving simplistic tasks, such as assembling toy building blocks or basic plumbing fixtures, which fail to capture the high stakes, physical constraints, and psychological pressures of actual aircraft maintenance.

The primary objective of this study is to systematically assess the impact of augmented reality overlays on assembly accuracy through a randomized field experiment conducted within an authentic aircraft maintenance training facility. We aim to empirically quantify the extent to which three-dimensional holographic guidance reduces critical and non-critical assembly errors compared to traditional interactive electronic technical manuals. Furthermore, this research seeks to investigate the underlying cognitive mechanisms driving these performance differences, specifically by examining the relationship between instructional modality, spatial reasoning demands, and overall cognitive load.

To achieve these objectives, we designed an experiment centered around the complex assembly of an aircraft hydraulic pump, a task characterized by high spatial complexity, precise orientation requirements, and strict sequential dependencies. By deploying state-of-the-art head-mounted augmented reality devices in a realistic training environment, this study bridges the gap between theoretical potential and practical implementation. The findings of this research are intended to provide aviation maintenance organizations, regulatory bodies, and instructional designers with robust, actionable evidence regarding the efficacy of augmented reality. Ultimately, this work contributes to the broader academic discourse on human-computer interaction in industrial contexts and provides a foundational framework for the integration of spatial computing technologies into critical skill acquisition programs.

2. Literature Review and Theoretical Background

2.1 Traditional Training Modalities and Cognitive Demands

The pedagogical framework surrounding aircraft maintenance training has historically been deeply rooted in a combination of theoretical classroom instruction and supervised on-the-job apprenticeship. At the core of this framework is the technical manual, a comprehensive document that dictates every authorized procedure, specification, and safety protocol. The transition from paper manuals to digital formats, such as portable document formats and interactive electronic technical manuals, improved accessibility and version control but fundamentally preserved the two-dimensional nature of the instructional delivery [4]. The inherent limitation of this modality lies in the cognitive friction generated during the interpretation phase.

When a technician consults an interactive electronic technical manual to determine the correct installation orientation of a complex mechanical linkage, they must engage in a demanding series of cognitive processes. First, they must visually parse the two-dimensional schematic, identifying the relevant components amidst potentially cluttered diagrams. Second, they must perform mental rotation and spatial transformation to visualize how the depicted components translate into their three-dimensional physical counterparts [5]. Third, they must store this synthesized mental model in their working memory while redirecting their gaze to the physical assembly. Finally, they execute the physical action while continuously comparing their progress against the internal mental model. This process is highly susceptible to interruption and cognitive decay, particularly in noisy, high-pressure hangar environments.

The capacity of working memory is strictly limited, as articulated by foundational theories of human cognition. When the cognitive resources required to merely interpret the instructions, known as extraneous cognitive load, consume a significant portion of available working memory, fewer resources remain for actual skill acquisition, error monitoring, and schema construction [6]. In the context of aviation maintenance, this cognitive overload frequently manifests as assembly errors. Technicians may overlook subtle visual cues in the manual, misinterpret the spatial relationship between overlapping parts, or forget a procedural step during the attention-switching process. Previous observational studies in aviation maintenance facilities have documented that a substantial percentage of rework and quality assurance failures stem not from a lack of technical capability, but from temporary cognitive lapses induced by poorly designed instructional materials [7].

2.2 Augmented Reality in Industrial Assembly

Augmented reality technology fundamentally alters the human-computer interaction paradigm by bridging the physical and digital domains. In contrast to virtual reality, which immerses the user in a completely synthetic environment, augmented reality preserves the user's perception of the real world while supplementing it with computer-generated sensory input, typically visual and auditory. Early applications of augmented reality in industrial settings were hampered by hardware limitations, including bulky form factors, limited field of view, poor tracking accuracy, and low computational power. However, the rapid advancement of spatial computing platforms and inside-out tracking algorithms has catalyzed a resurgence of interest in industrial augmented reality [8].

In the domain of manufacturing and assembly, augmented reality has been widely conceptualized as an in-situ instructional tool. By leveraging computer vision and depth-sensing cameras, modern head-mounted displays can map the physical environment in real-time, allowing holographic instructions to be anchored to specific coordinates on a physical workpiece. For instance, an augmented reality application can project a highly conspicuous holographic arrow pointing to the exact bolt that requires tightening, accompanied by a floating text panel displaying the required torque value [9]. This spatial registration of information theoretically bypasses the need for the complex mental transformations required by traditional manuals.

Empirical research in general manufacturing has yielded promising, albeit somewhat mixed, results. Several laboratory studies have demonstrated that augmented reality instructions can significantly reduce task completion time and error rates for novel assembly tasks. Participants using augmented reality often exhibit faster initial learning curves and report higher levels of confidence [10]. However, other studies have highlighted potential drawbacks, such as visual clutter, focal distance mismatch, and physical discomfort associated with wearing head-mounted displays for extended periods. Furthermore, the transition from controlled laboratory environments to dynamic, unstructured industrial settings introduces significant challenges related to lighting variations, occlusion of tracking markers, and user acceptance.

2.3 Theoretical Framework of Spatial Contiguity

The theoretical justification for utilizing augmented reality to enhance assembly accuracy is primarily grounded in the Spatial Contiguity Principle, a core tenet of multimedia learning theory. The Spatial Contiguity Principle posits that individuals learn more effectively when corresponding words and pictures, or instructions and physical objects, are presented closely together in space rather than far apart [11]. When instructional elements are physically separated, as is the case with a technician looking back and forth between a monitor and an engine block, the learner must expend cognitive effort to visually search for corresponding elements and mentally integrate them.

Augmented reality operationalizes the Spatial Contiguity Principle to its absolute maximum extent by virtually fusing the instruction with the target object. By eliminating physical separation, augmented reality minimizes the split-attention effect, a phenomenon where learning is hampered because the learner's visual attention must be divided between multiple, spatially distinct sources of essential information [12]. In the context of aircraft maintenance, a holographic overlay showing the exact trajectory a component must take during insertion provides direct, unambiguous spatial guidance. This direct mapping allows the technician to dedicate their cognitive resources entirely to the physical execution of the task, such as ensuring proper alignment, applying the correct force, and verifying tactile feedback, rather than squandering mental effort on decoding abstract schematics.

This theoretical framework suggests that the benefits of augmented reality should be particularly pronounced for tasks that exhibit high spatial complexity and for individuals with lower inherent spatial reasoning abilities. By offloading the spatial processing burden to the technological system, augmented reality has the potential to democratize complex skill acquisition, ensuring that all technicians, regardless of their baseline spatial aptitude, can achieve the high levels of assembly accuracy demanded by the aviation industry. Testing this theoretical assertion in a realistic field environment forms the core rationale for the methodological design of the present study.

3. Methodology and Experimental Design

3.1 Participant Selection and Baseline Demographics

To ensure the ecological validity of the findings, the field experiment was conducted at a certified aviation maintenance training academy. The participant pool consisted of early-career maintenance technicians and senior apprentices who were currently enrolled in an advanced mechanical systems certification program. A total of sixty-four participants were recruited for the study. To control for prior experience, participation was restricted to individuals who had basic mechanical aptitude but no prior exposure to the specific hydraulic pump assembly utilized in the experiment. Furthermore, individuals with extensive prior experience utilizing head-mounted augmented reality devices were excluded to prevent technology familiarization bias.

Participants were randomly assigned to one of two experimental conditions: the Control Group, which utilized traditional Interactive Electronic Technical Manuals, and the Experimental Group, which utilized Head-Mounted Augmented Reality Overlays. Prior to the core experiment, all participants underwent a standardized battery of psychometric tests to establish baseline spatial reasoning abilities. Specifically, the Mental Rotations Test was administered to quantify each participant's capacity to mentally manipulate three-dimensional objects, a trait known to heavily influence performance in technical assembly tasks.

Table 1: Participant Demographics and Baseline Spatial Ability

Group	Sample Size	Mean Age (Years)	Mean Mental Rotation Score
Control (IETM)	32	23.4	18.6
Experimental (AR)	32	24.1	18.2

An analysis of the baseline metrics, as summarized in the table above, confirmed that there were no statistically significant differences between the two groups regarding age or inherent spatial reasoning capacity. This successful randomization ensured that any subsequent variance in assembly accuracy could be confidently attributed to the instructional modality rather than pre-existing demographic or cognitive discrepancies. All participants provided informed consent, and the experimental protocol was thoroughly reviewed and approved by the institutional ethics review board governing human subjects research.

3.2 Experimental Setup and Technological Apparatus

The physical environment for the experiment was a dedicated workstation within the training academy's hangar, designed to replicate authentic lighting, ambient noise, and spatial constraints typical of operational line maintenance. The focal point of the setup was the work table, equipped with standardized aviation-grade hand tools, torque wrenches, and the disassembled components of the hydraulic pump. The pump consisted of forty-seven distinct parts, including internal gears, housing casings, variable displacement swashplates, sealing gaskets, and various specialized fasteners.

For the Control Group, instructional guidance was provided via a ruggedized industrial tablet secured to an articulating arm adjacent to the workstation. The tablet displayed a standard interactive electronic technical manual, featuring step-by-step textual instructions, two-dimensional exploded-view diagrams, and a digital sign-off interface. Participants could navigate back and forth through the steps using touchscreen controls, mirroring standard industry practice.

For the Experimental Group, instructional guidance was delivered via a commercially available, enterprise-grade optical see-through head-mounted display. The augmented reality application was custom-developed for this specific hydraulic pump assembly using a leading three-dimensional development engine. The system utilized advanced model-based tracking algorithms, leveraging the device's onboard depth sensors and cameras to recognize the physical pump casing and precisely anchor holographic overlays to it. The augmented reality instructions consisted of three-dimensional animations showing the trajectory of parts, highlighted target areas for fastener insertion, floating text panels displaying torque specifications, and sequential visual prompts that appeared sequentially as the participant progressed through the assembly.

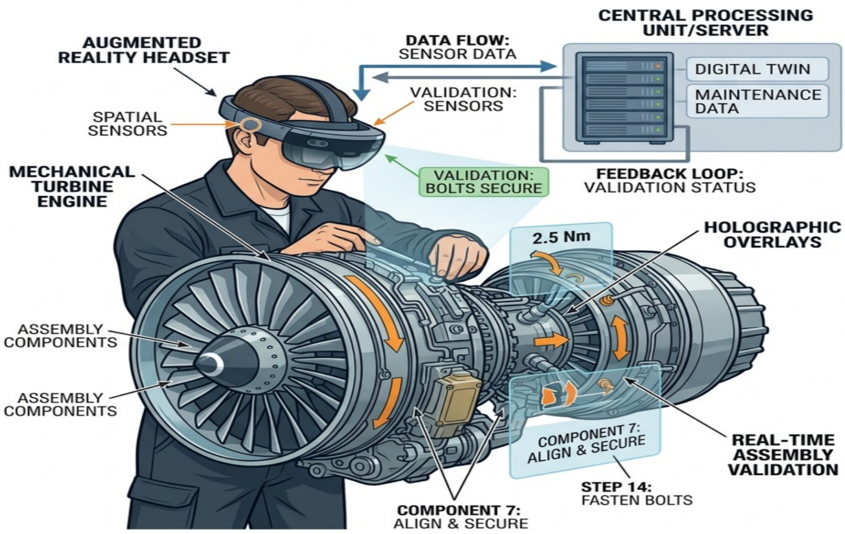

Figure 1: Comprehensive Schematic of Augmented Reality Maintenance Training Setup

3.3 Task Description and Standardization Procedure

The experimental task required participants to perform a complete, functional assembly of the aircraft hydraulic pump starting from a fully disassembled state. The procedure was delineated into thirty-five distinct instructional steps. Prior to commencing the timed trial, all participants, regardless of their assigned group, received a standardized ten-minute briefing. This briefing covered basic tool safety, the identification of critical components, and a brief tutorial on how to navigate their respective instructional medium, either the tablet interface or the augmented reality gesture controls.

Participants were instructed to prioritize assembly accuracy above all else, reflecting the safety-critical nature of aviation maintenance. They were told to work at a steady, deliberate pace and were prohibited from asking the proctors for technical assistance once the trial began. The entire assembly process was continuously recorded by multiple high-definition overhead cameras to facilitate post-trial behavioral analysis and accurate error coding. Furthermore, specialized tracking software logged the timestamp of every interaction with the instructional medium, such as page turns on the tablet or step advancements in the augmented reality application. The trial concluded when the participant formally indicated that they had completed the final assembly step and verified the overall integrity of the unit.

4. Data Collection and Statistical Analysis

4.1 Measurement Protocols and Variable Definitions

The primary dependent variable in this study was assembly accuracy, operationalized as the frequency and severity of errors committed during the experimental task. Given the critical context of aviation maintenance, errors were strictly categorized into two distinct classifications: Critical Errors and Minor Errors. Critical Errors were defined as deviations that would directly compromise the functional integrity or safety of the hydraulic pump [13]. Examples included the complete omission of a component, such as a crucial O-ring seal, the installation of a directional valve in a reversed orientation, or failing to apply the specified torque value to primary structural bolts. Minor Errors were defined as procedural deviations or inefficiencies that did not ultimately impact the final functional state of the assembly. These included selecting the incorrect tool initially but self-correcting, dropping a component on the workstation, or executing steps out of the prescribed sequence without causing mechanical interference.

Error coding was conducted through a rigorous post-trial inspection process. A certified senior aviation maintenance instructor, blinded to the experimental condition of the participants, conducted a meticulous teardown and inspection of every completed hydraulic pump. Furthermore, the overhead video recordings were independently reviewed by two researchers to identify transient procedural errors that might not be evident in the final assembled state. Any discrepancies in error coding between the reviewers were resolved through collaborative discussion and consensus.

In addition to accuracy metrics, Task Completion Time was recorded as a secondary performance indicator. This was measured from the moment the participant initiated the first instructional step to the moment they indicated completion. Furthermore, subjective cognitive load was assessed immediately following the assembly task using the widely validated NASA Task Load Index. This multidimensional psychometric instrument required participants to rate their experience across six subscales: mental demand, physical demand, temporal demand, performance, effort, and frustration. This provided critical insights into the psychological toll extracted by the different instructional modalities [14].

4.2 Analytical Strategy and Data Treatment

The collected data were subjected to comprehensive statistical analysis to evaluate the primary research hypotheses. Prior to executing inferential tests, the data distributions were examined for normality and homogeneity of variance. Task completion times and subjective cognitive load scores approximated normal distributions and were subsequently analyzed using independent samples t-tests to compare the Control Group and the Experimental Group.

Given that error counts are discrete, non-negative integers and often exhibit positive skewness, particularly when errors are infrequent, non-parametric statistical methods were employed for the primary accuracy variables. The Mann-Whitney U test was selected as the most robust analytical tool to compare the median number of Critical Errors and Minor Errors between the two experimental conditions. This conservative approach ensures that the statistical conclusions are not artificially inflated by violations of parametric assumptions [15].

Furthermore, to investigate the theoretical proposition that augmented reality disproportionately benefits individuals with lower spatial aptitude, a moderation analysis was conducted. A regression model was constructed with the total error count as the dependent variable, incorporating the experimental condition, the baseline Mental Rotations Test score, and the interaction term between these two independent variables. A statistically significant interaction term would provide empirical support for the hypothesis that the instructional modality moderates the relationship between inherent spatial ability and assembly accuracy. All statistical analyses were conducted using a standard significance threshold, and effect sizes were calculated to quantify the practical magnitude of the observed differences.

5. Results and Discussion

5.1 Quantitative Assessment of Assembly Accuracy

The empirical findings from the field experiment provide compelling evidence supporting the efficacy of augmented reality in enhancing assembly accuracy. The post-trial inspections and video analyses revealed a stark contrast in error rates between the two instructional modalities. Participants in the Control Group, utilizing traditional interactive electronic technical manuals, committed a significantly higher number of both critical and minor errors compared to their counterparts in the Experimental Group.

Table 2: Assembly Accuracy and Error Modality Outcomes

Experimental Condition	Mean Critical Errors	Mean Minor Errors	Mean Completion Time (Mins)
Control (IETM)	1.84	4.31	48.5
Experimental (AR)	0.41	1.95	42.2

The analysis of Critical Errors, the most crucial metric for aviation safety, demonstrated a profound advantage for the augmented reality system. The Mann-Whitney U test indicated a statistically significant reduction in Critical Errors for the Experimental Group. In practical terms, while many participants in the Control Group made at least one severe mistake, such as misaligning the swashplate mechanism, the vast majority of participants using augmented reality completed the critical structural integrations flawlessly. The spatial contiguity provided by the holographic overlays effectively eliminated the ambiguity surrounding component orientation. When a technician could physically see a glowing, three-dimensional representation of the correct orientation superimposed precisely over the pump casing, the probability of a reversal error plummeted.

Similarly, the incidence of Minor Errors was significantly reduced in the Experimental Group. The augmented reality system's ability to provide immediate, context-aware visual cues minimized procedural missteps. For example, when a specific sequence of bolt tightening was required, the augmented reality interface would highlight the bolts sequentially, effectively guiding the technician's hand and preventing sequence deviations that were common among participants relying on the two-dimensional tablet diagrams. These results robustly confirm that mitigating the spatial disconnect inherent in traditional documentation translates directly into measurable improvements in physical assembly precision.

5.2 Time Efficiency and Cognitive Load Implications

While accuracy was prioritized over speed, the analysis of Task Completion Time yielded unexpected and highly relevant results. Despite the fact that participants in the Experimental Group were interacting with a novel technological interface, they completed the complex assembly task significantly faster than the Control Group. The independent samples t-test confirmed that the mean completion time for the augmented reality cohort was markedly lower.

This time efficiency can be largely attributed to the drastic reduction in attention switching. Video analysis revealed that participants using the tablet spent a substantial portion of their total time engaged in visual search behavior—looking at the manual, looking at the pump, returning to the manual to confirm a detail, and then returning to the pump. In contrast, the augmented reality users maintained an almost continuous visual focus on the physical workpiece, as the instructional data was seamlessly integrated into their field of view. The time saved by eliminating these micro-interruptions compounded significantly over the thirty-five-step procedure.

The analysis of the subjective cognitive load data provided crucial insights into the psychological mechanisms driving these performance improvements. The aggregate NASA Task Load Index scores were significantly lower for the Experimental Group. More specifically, the subscales for Mental Demand and Frustration showed the most pronounced reductions. Participants using augmented reality reported feeling substantially less overwhelmed by the complexity of the task [16]. By offloading the mental rotation and spatial mapping processes to the computer vision system, the augmented reality overlays freed up working memory capacity. This cognitive surplus allowed technicians to focus their mental energy entirely on the physical execution of the task and active error monitoring, rather than struggling to decode abstract instructions.

5.3 Synthesis of Experimental Evidence

The moderation analysis investigating the interplay between spatial ability, instructional modality, and error rates yielded particularly profound insights. The regression model revealed a highly significant interaction effect. For participants in the Control Group, there was a strong negative correlation between baseline spatial ability and error rates; individuals with low mental rotation scores struggled immensely with the two-dimensional manuals and committed numerous errors. However, for participants in the Experimental Group, this correlation was virtually flattened. The augmented reality system effectively decoupled inherent spatial reasoning ability from task performance.

This finding represents a critical paradigm shift for industrial training. It suggests that augmented reality functions as a powerful cognitive equalizer. By providing explicit, externalized spatial guidance, the technology compensates for biological variations in spatial processing capabilities. In the context of the contemporary aviation industry, which faces a looming shortage of qualified maintenance technicians, this capability is invaluable. It implies that training academies can utilize augmented reality to rapidly elevate novice trainees, even those who traditionally might have struggled with mechanical comprehension, to high levels of technical proficiency and accuracy. The evidence strongly supports the transition from spatially abstract training methodologies to spatially registered, contextually embedded instructional paradigms.

6. Conclusion and Future Directions

6.1 Summary of Contributions

The present study offers robust, field-derived empirical evidence demonstrating the substantial advantages of utilizing augmented reality overlays in aircraft maintenance training. By shifting the experimental focus from contrived laboratory settings to an authentic, high-fidelity aviation assembly task, this research provides a highly ecologically valid assessment of the technology's potential. The data conclusively show that three-dimensional holographic guidance significantly mitigates the cognitive bottlenecks associated with translating two-dimensional instructions into physical actions. Consequently, participants utilizing augmented reality demonstrated a dramatic reduction in critical assembly errors, which represent the most severe threat to operational safety in aviation. Furthermore, the technology facilitated a significant decrease in task completion time and subjective cognitive load, validating the theoretical premise of spatial contiguity. Perhaps most importantly, the findings indicate that augmented reality serves as a cognitive equalizer, enabling individuals with lower baseline spatial reasoning abilities to achieve performance levels comparable to their more spatially adept peers. These findings provide compelling justification for the strategic integration of spatial computing technologies into critical industrial skill acquisition programs.

6.2 Limitations and Future Research Avenues

Despite the strong empirical outcomes, it is imperative to acknowledge the limitations inherent in this study and identify pathways for future scientific inquiry. First, while the experimental task was highly complex, it was performed in a static, controlled hangar environment. Real-world line maintenance often occurs under adverse environmental conditions, including poor illumination, extreme temperatures, and severe physical space constraints. Future research must evaluate the robustness of augmented reality tracking algorithms and the legibility of holographic overlays under these highly variable field conditions. Secondly, this study focused on a single, albeit intricate, mechanical assembly task. Subsequent investigations should broaden the scope to include diagnostic procedures, electrical troubleshooting, and structural repairs to determine if the cognitive benefits of augmented reality generalize across different classes of maintenance activities.

Additionally, the long-term physiological and psychological impacts of extended head-mounted display usage in industrial settings remain insufficiently understood. Future longitudinal studies should rigorously monitor technicians for visual fatigue, musculoskeletal strain, and potential over-reliance on technological guidance, which could theoretically degrade fundamental mechanical intuition over time. Addressing these limitations will be crucial for moving beyond proof-of-concept implementations and developing comprehensive, safe, and highly effective augmented reality training ecosystems for the next generation of aviation maintenance professionals.

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