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WIP: Studying Quantitative Cognitive and Performance Metrics in AR/VR Training for Manufacturing – Toward a Load-Optimized Immersive Design Framework

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WIP: Studying the Quantitative Cognitive and Performance Metrics in AR/VR Training in Manufacturing: Proposal for Load-Optimized Immersive Design

Abstract

This work in progress describes the study of the main challenges when dealing with manufacturing is to effectively communicate complex processes to technicians and workers. Generally, static visual instructions are not enough to help employees understand the manufacturing steps, generating inefficiency and mistakes. Immersive technologies-AR and VR-offer new opportunities through their interactive interfaces. However, in spite of this, they have seen very limited implementation within the U.S. manufacturing sector because of high cognitive load due to poor system design. This research applies Cognitive Load Theory to the design of AR/VR training, reducing extraneous cognitive load, thereby improving task performance and retention. Using Meta Quest 3 and HoloLens, modular scenario tests were conducted to evaluate how AR/VR interfaces impact fundamental engineering graphics competencies, such as 3D spatial visualization and CAD-to-physical model translation. Additionally, demographic data (including gender, academic level, and prior graphics experience) were tracked to identify correlations between student background and cognitive load. [1]

Background

The manufacturing domain grapples with enormous barriers in the area of knowledge transfer, especially regarding the very complicated and intricate procedural tasks. Usual static instructions rarely fulfill the requirements for a complete understanding by making things more complicated thus causing more errors and slowing down the operations. On the other hand, immersive technology like Augmented Reality (AR) and Virtual Reality (VR) promise a revolution in the training process, but their use in the U.S. is hindered by complex design limitations that induce significant mental fatigue. Operators interacting with suboptimal system designs often experience cognitive overload which is the opposite of the technology's intended benefits. A number of previous studies have shown that industrial maintenance and machining processes are still the areas where the highest precision is essential; nevertheless, the AR overlays sometimes reaching the user's natural field of view can cause a neurophysiological strain turning to inhibition of performance. Also, the high pace of technological change in the manufacturing sector entails the onboarding systems to be simultaneously efficient and capable of overcoming the "split-attention effect," where the operator has to pay attention to the physical task and the digital instruction manual at the same time.

The media shift from traditional to AR involves the spatial information processing to be done in a different way, usually, the visual density has to be reduced to avoid causing both safety and accuracy problems. Research into Extended Reality (XR) requires a longitudinal approach, and the first step is to map out the physiological impact spectrum of these tools—eye strain to mental fatigue—so that sustainable training models can be built. The evolution of the manufacturing workforce goes hand in hand with the demand for "simple and brief" instructional designs that are immune to the cognitive "choke points" common in non-adaptive, static training sequences [3], [8]. As shown from the research done in Simple Brief Instructions in VR training and teaching this graph below denotes group means from their analysis that will help guide in a similar style this papers research;

		LowIL-LowEL	HighIL-LowEL	LowIL-HighEL	HighIL-HighEL
Mental Workload	Adaptive Training	7.50 (SD = 4.03)	8.81 (SD = 3.88)	7.92 (SD = 3.72)	8.82 (SD = 3.72)
	Fixed Training	7.94 (SD = 3.57)	9.20 (SD = 3.66)	8.58 (SD = 3.79)	9.92 (SD = 4.41)
Retention Test Error Rate	Adaptive Training	28.60 (SD = 14.90)	30.90 (SD = 14.20)	31.80 (SD = 16.10)	28.10 (SD = 17.50)
	Fixed Training	32.30 (SD = 17.40)	32.10 (SD = 18.60)	31.40 (SD = 20.50)	28 (SD = 16.10)
Training time (minutes)	Adaptive Training	7.65 (SD = 2.93)	10.40 (SD = 3.87)	9.67 (SD = 3.83)	12.20 (SD = 4.31)
	Fixed Training	9.02 (SD = 2.90)	11.50 (SD = 2.85)	10.70 (SD = 3.24)	13.70 (SD = 5.06)

Figure 1.1 Index Table from [3] Simple Brief Instructions in VR Training.

Beyond manufacturing training, this research directly relates to engineering graphics education, where students are required to develop competencies in orthographic projection, section views, 3D spatial visualization, and CAD-to-physical model translation. These foundational skills require substantial mental transformation and spatial reasoning, particularly in early graphics coursework. Many students experience difficulty when converting 2D representations into 3D mental models, often resulting in increased cognitive strain and errors in interpretation. By applying Cognitive Load Theory (CLT) to XR interface design, this study frames immersive technologies not only as industrial training tools, but also as cognitive support systems that can reduce unnecessary mental processing during spatial reasoning tasks central to engineering graphics curricula.

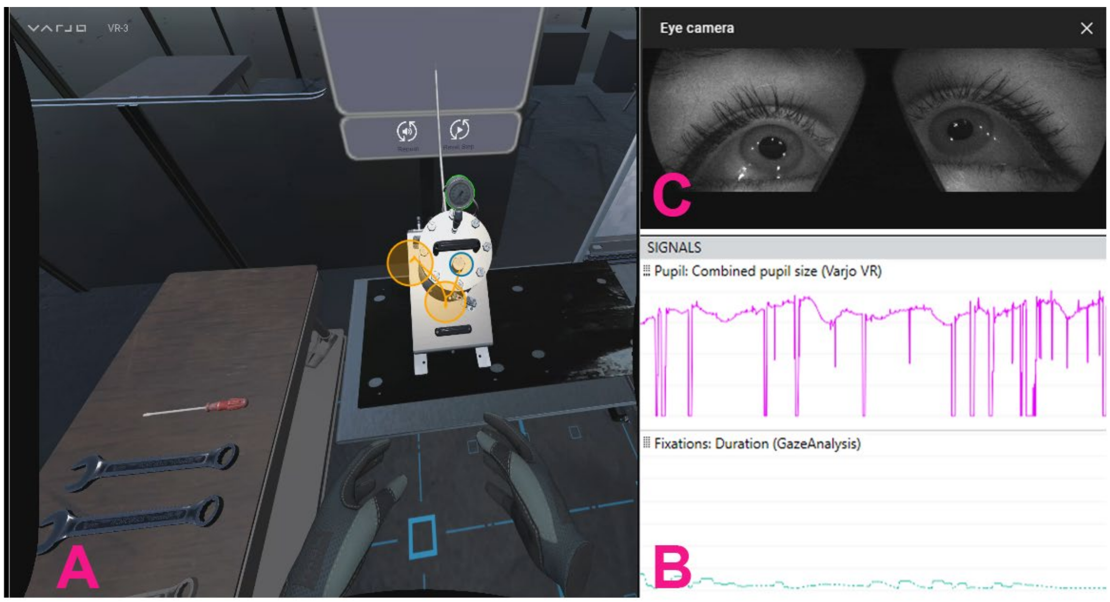
Purpose

While existing studies have separately addressed cognitive load in AR through interface design and cybersickness in VR through locomotion techniques, there is a lack of integrated frameworks that simultaneously address both visual extraneous load and vestibular conflict. Current literature rarely evaluates the synergistic effect of 'minimalist' Mixed Reality (MR) anchoring combined with slip-mill locomotion on retention and error rates in manufacturing training. This study bridges that gap by focusing on the use of Cognitive Load Theory (CLT) in the design of AR/VR training modules in manufacturing for both graphic design and machine training in student demographics. The main goal is to make the extraneous cognitive load as little as possible so that the task performance, information retention, and training effectiveness will be improved. This research will be based on the analysis of both subjective and physiological indicators of mental effort and will aim at a contribution to the understanding of the relation between interface complexity and user outcomes in manufacturing aid scenarios. [1], [6].

Framework

Cognitive Load Theory (CLT) is the theoretical foundation of this study and it classifies mental effort into three types: intrinsic, extraneous, and germane load. The present research has narrowed its focus to the limitation of extraneous load—the mental processing that is not necessary and caused by poor interface design—which will enable the cognitive capacity created to be used for building permanent procedural knowledge.

Some literature points to bridging the gaps in integrated graphics and Extended Realities (XR) like this topic where they show case a class over 2 years where students were introduced to various CAD software and learning materials and then introduced to using AR and VR for different specialties for the tools in graphics. The results and assessment section denoted that: ”based on the course experience and the comments shared by students in class, the research team concluded that integrating augmented reality (AR) can be particularly beneficial in the first part of the Engineering Graphics sequence, when students are introduced to the principles of technical drawing and orthographic projections. Virtual reality (VR), on the other hand, appears to be more effective for developing spatial understanding of floor plans and sections.” [9] Also previous studies show that a high extraneous load in XR is primarily caused by difficult visual overlays which lead the users to ignore the irrelevant data, thus causing increased pupil dilation and more mistakes [1], [2]. This research which is based on such findings goes one step further by introducing a Mixed Reality (MR) perspective where "minimalist anchoring" is the central design principle. The framework increases the efficiency of the technician by using MR to anchor 3D digital twins directly onto the physical machines reducing the spatial transformation effort required.



Figures 1.2 -4 Eye tracking research for load optimization. From [2]: (A) Processing data in iMotions Lab of a user in the VR training environment interacting with powder feeder; the yellow circles are fixations. (B) The mean pupil dilation signal for both eyes is pink, and the fixation duration signal is the blue color; both signals are processed in iMotions Lab. (C) User’s eyes captured in Varjo VR-3 eye tracking

Moreover, a desired use of the Omni One slip mill to solve the vestibular-visual conflict issue as a change to the framework. One of the main reasons why VR training has not been widely adopted is the issue of "cybersickness". This happens when the inner ear feels a stationary body while the eyes see movement, and this eventually leads to the loss of balance. In contrast to a motorized treadmill, the Omni One is a low-friction slip mill which lets users do natural walking movements in all direction without any traction-based propelling. The study is bypassing the whole thing through the use of slip mills technology, the study is going to ensure that lower body participation in reality is perfectly matched with virtual movement. This synchronization softens the inner ear conflict and mitigates the physiological conflict associated with motion sickness, allowing the trainee to is able to concentrate solely on manufacturing steps [6], [8]. This allencompassing technique unites multimodal feedback (visual and auditory) with physical participation so as to efficiently relieve the germane load necessary for the long-lasting retention of skill.

Methods

At present, modular training scenarios for courses that use CNC machining operations are being developed using a digital twinning approach within XR environments. In this study, digital twinning refers to anchoring 3D CAD-based models and machining process information directly onto physical or virtual machine environments to support secondary part verification and procedural training. In addition to CNC verification tasks, one module is specifically designed to target engineering graphics competencies. In this scenario, participants interpret orthographic projections and section views, then match those 2D drawings to 3D digital twins within the XR environment. The task evaluates spatial visualization ability, dimensional interpretation, and CAD-to-physical model translation—skills commonly assessed in introductory and intermediate engineering graphics courses. This allows the study to examine how XR interface complexity influences cognitive load during graphics-based spatial reasoning tasks. These scenarios are being created using Unity as the primary 3D development platform, with the capability to integrate other engines such as Unreal Engine or proprietary CNC simulation software (e.g., Haas platforms) if required.

The system is designed for compatibility with the VR condition using Meta Quest 3 and the AR condition using Microsoft HoloLens. For navigation-based VR tasks, the system integrates the Omni One slip mill to support natural walking movement and reduce vestibular–visual conflict during immersive interaction.

A between-subjects experimental design will be employed, in which participants are randomly assigned to one interface condition to minimize learning and carryover effects across conditions.

The experimental design examines four primary interface parameters:

1. Overlay complexity (low vs. high)
2. Feedback modality (visual only vs. visual + audio)
3. Navigation structure (fixed sequence vs. multi-layer navigation)
4. Adaptivity (static interface vs. real-time adaptive interface)

These variables are manipulated to evaluate how interface design influences extraneous cognitive load under a Cognitive Load Theory (CLT) framework.

Overlay complexity will be operationalized based on the number, density, and layering of visual elements presented simultaneously within the user's field of view. Feedback modality will distinguish between visual-only cues and combined visual–auditory instructional prompts. Navigation structure will be defined by the degree of user control and branching (linear step progression versus hierarchical or multi-path navigation). Adaptivity will be implemented through system-driven interface adjustments triggered by real-time performance thresholds (e.g., error rate or task completion time).

Once scenario development is finalized, participants with varying levels of manufacturing and engineering graphics experience will be recruited and randomly assigned to training conditions. Demographic information, including gender, academic level, and prior graphics/CAD experience, will be collected to evaluate potential correlations with cognitive load and performance outcomes.

Participant experience level will be quantified using a pre-study questionnaire and treated as a covariate in statistical analyses to control for its influence on cognitive load and task performance.

Data collection will include three primary categories of measures:

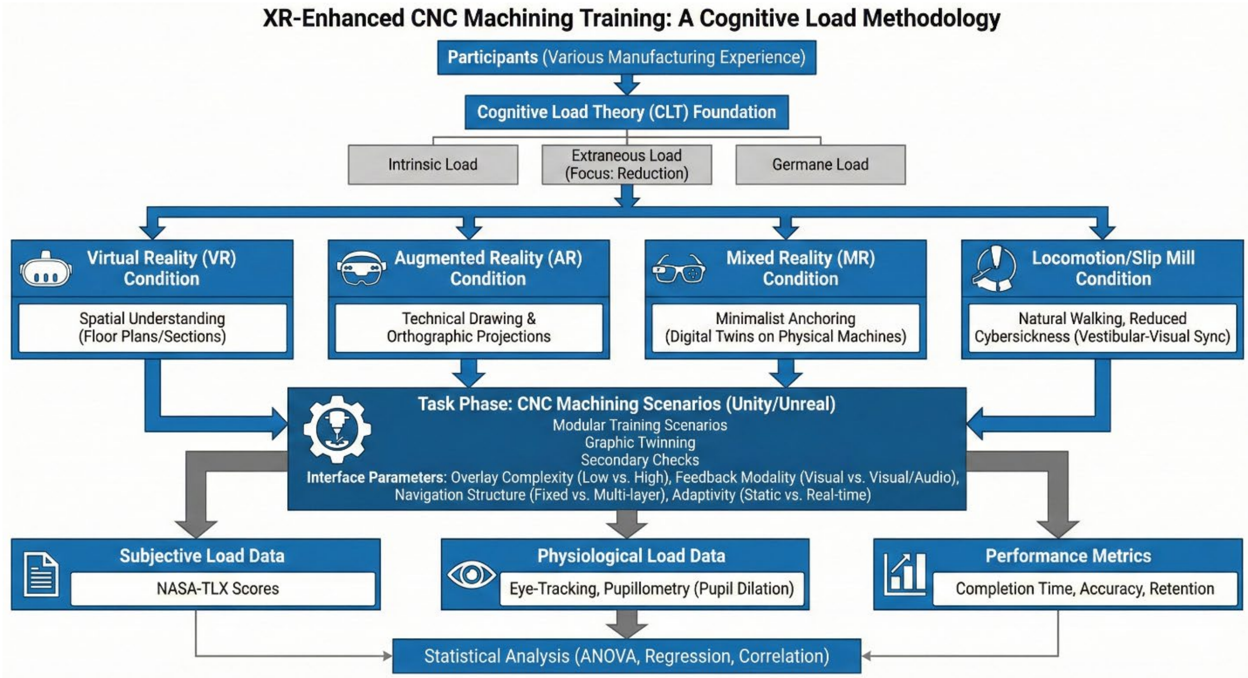
- Subjective cognitive load: NASA-TLX scores [5][10]
- Physiological cognitive load: eye-tracking metrics and pupillometry [2], [6]
- Performance metrics: task completion time, accuracy (error rate), and retention assessments

Eye-tracking and pupillometry data will be collected using integrated headset sensors (where available) or external tracking systems, with calibration conducted prior to each session and sampling rates recorded to ensure measurement consistency.

Each participant will complete a fixed number of trials per assigned condition (e.g., 3–5 tasks per module), with individual task durations and total session time standardized across participants. Task order will be randomized where applicable to reduce ordering effects.

All multimodal data streams (subjective, physiological, and performance-based) will be time-synchronized using system-generated timestamps to ensure alignment between interaction events and recorded measures. NASA-TLX assessments will be administered immediately following each task to capture task-specific cognitive load.

Statistical analyses will include ANOVA to compare interface conditions, regression modeling to evaluate relationships between interface variables and cognitive load, and correlation analyses to examine associations between demographic factors and performance. These analyses will determine how variations in XR interface design impact cognitive load, task performance, and training effectiveness. The below figure 1.5 show cases a flow of how we intend to perform through the methodology of the study.



Figures 1.5 Methodology flowchart. generated by Google Gemini (Nano Banana 2) on March 2026.

Preliminary results

Based on past findings in the reviewed literature there is indication that simplified and adaptive user interfaces significantly reduce cognitive load across industrial applications. Further research from 2025 demonstrates that brief, adaptive instructions within VR training yield superior performance compared to static, complex overlays [3]. Our future results should also corroborate this, however we also want to show that new technology and new methodology shows further improvement as we reduce the cognitive load on workers and students in XR environments. As neurophysiological evaluations confirm that AR interactions in maintenance tasks trigger high cognitive demands that can be mitigated through optimized user interface design [1]. Past comparative analyses suggest that while AR improves machining instruction and graphic interaction, its effectiveness is contingent on managing visual density [4]. Eye-tracking data from complex VR environments shows that pupillary response is a reliable detector of cognitive overload, reinforcing the need for adaptive sequences that respond to user stress in real-time [2].

We expect these new results to shift more favorably due to the integration of Mixed Reality (MR) anchoring and slip mill technology for a new index that will help both Scholastic and Manufacturing fields. While previous documentation notes that AR improves instruction but risks visual interference, our use of MR-anchored 3D twins is expected to further decrease error rates by eliminating the need for 2D-to-3D mental translation. Furthermore, whereas existing literature acknowledges physiological strain and "cybersickness" as limiting factors for training duration, the implementation of the Omni One slip mill is expected to deviate from these results by showing a marked decrease in vestibular-induced cognitive load. This should allow for longer training sessions with higher germane load and better retention compared to the static or joystick-based navigation utilized in the referenced studies [7], [8].

Conclusions

This research provides a framework for load-optimized immersive training in the manufacturing industry. By combining CLT with MR anchoring and the Omni One slip mill, the study addresses both mental and physiological barriers to training. This framework offers a structured approach for integrating XR technologies into engineering graphics instruction while maintaining cognitive efficiency during spatial reasoning tasks. By explicitly targeting extraneous cognitive load in 2D-to-3D translation and orthographic interpretation activities, the study contributes to ongoing efforts to improve spatial visualization development without introducing unnecessary interface complexity. Future stages will consider long-term effects on skill retention and the integration of live dashboards. In the end, it is intended to provide the workforce with AR/VR solutions that are scalable, evidence-based, and capable of accelerating onboarding and improving operational safety.

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