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# Scaffolding tacit knowledge transfer via ontology-driven non-immersive virtual reality: an empirical analysis of skill acquisition in vocational training

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**ABSTRACT**

Traditional vocational training struggles to transfer “tacit knowledge” – intuitive, context-dependent expertise required for complex spatial planning, motor coordination, and environmental hazard detection. To address this bottleneck in solar photovoltaic (PV) installation training, this study proposes an ontology-based non-immersive virtual reality (VR) system that externalizes expert cues into a digital learning environment. Grounded in the Solar PV Knowledge Ontology, the system uses a desktop-based “Magic Window” interface designed to reduce technology-related barriers. A quasi-experimental design was implemented with 65 engineering students assigned by intact instructional conditions to an experimental group using the interactive VR system or a control group receiving conventional instruction. Assessment instruments were mapped to the ontology dimensions and measured explicit theoretical knowledge, practical procedural skill performance, and blueprint interpretation. The experimental group significantly outperformed the control group across assessed dimensions. These findings suggest that combining formal knowledge modeling with non-immersive VR may support the novice-to-expert transition by preserving spatial context while avoiding interface burdens associated with highly immersive systems. However, cognitive load was used as an instructional design framework rather than as a directly measured outcome in this study. The study provides a scalable framework for digital vocational training and highlights the pedagogical value of aligning interactive learning environments with explicit knowledge structures.

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## 1. Introduction

### *1.1. Background and motivation*

Mastering the nuances of highly technical vocational fields, such as solar photovoltaic (PV) installation, requires technicians to acquire substantial “tacit knowledge.” This concept, articulated by Polanyi (1966), describes human expertise that is internalized, intuitive, and difficult to articulate, codify, or transfer through traditional text-based manuals or static two-dimensional diagrams. Within specific operational contexts, tacit knowledge encompasses the ability to orient oneself spatially on complex, steeply pitched rooftops, the capacity for rapid environmental hazard detection, and the fine-motor coordination required during the assembly and wiring of fragile modules.

Historically, traditional apprenticeship models and on-the-job shadowing have served as the primary vehicles for transferring this elusive type of knowledge, relying heavily on prolonged, face-to-face observation and physical mimicry. However, as the demand for scalable training grows, these conventional pedagogical models are revealing severe structural limitations. On-site training is increasingly restricted by severe safety risks, equipment and insurance costs, the logistical challenges of coordinating large student cohorts, and a scarcity of accessible, real-world training sites suitable for novices. In photovoltaic education specifically, recent reviews have noted growing interest in VR-based approaches for renewable-energy training, while also emphasizing the need for careful instructional design and empirical validation (Alqallaf & Ghannam, 2024). Furthermore, in regions like Taiwan, traditional apprenticeship-based skill transfer is challenged

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by a declining birth rate and a growing aversion among youth toward working in harsh, high-temperature rooftop environments. Consequently, modern vocational education institutions face an urgent need to develop scalable digital instructional solutions capable of representing expert knowledge without exposing learners to the physical hazards of active construction sites.

### 1.2. Research problem: the knowledge acquisition bottleneck

A persistent and formidable challenge in the development of intelligent tutoring systems and digital vocational training platforms is the phenomenon known as the "knowledge acquisition bottleneck," initially identified by Feigenbaum (1977). This bottleneck encapsulates the extreme difficulty of extracting an expert's deeply internalized, intuitive understanding of a physical domain and successfully encoding that fluid expertise into a structured, computable digital learning system.

While VR technologies have been widely proposed for situated and spatial training, much of the current literature and commercial application still emphasizes high-fidelity or gamified experiences rather than structured, pedagogically explicit Knowledge Engineering (KE) approaches. Furthermore, the integration of highly immersive VR – specifically systems using head-mounted displays (HMDs) – has generated academic debate regarding the trade-off between psychological immersion and learning efficacy. Prior research indicates that fully immersive VR may increase presence while also introducing interface complexity, novelty effects, and cyber-sickness risks that can contribute to extraneous cognitive load for novices (Makransky et al., 2019; Radianti et al., 2020; Slater & Sanchez-Vives, 2016). Therefore, a critical gap exists concerning the design and empirical validation of non-immersive desktop VR systems that use domain-specific instructional knowledge structures to scaffold technical learning while reducing technology-related instructional barriers.

### 1.3. Objectives and contribution

To systematically address these multifaceted pedagogical and technological challenges, this study conceptualizes, develops, and validates an Ontology-Based Non-Immersive VR System specifically tailored for solar PV vocational training. Unlike generic 360-degree video players that present rich but unstructured visual environments, the proposed system is deeply grounded in a domain-specific "Solar PV Knowledge Ontology". This architectural framework systematically categorizes complex learning targets into explicit regulatory rules and tacit spatial cues, linking them directly to interactive digital overlays.

The specific theoretical and practical contributions of this study are threefold. First, regarding ontological modeling, the study defines a hierarchical instructional knowledge structure for solar installation, mapping relationships between formal regulatory codes (explicit knowledge) and situated spatial skills (tacit/procedural knowledge). Second, concerning system architecture, the research proposes and evaluates a lightweight, web-based VR architecture using a desktop "Magic Window" interface. This design choice was intended to maximize institutional accessibility across diverse hardware while managing extraneous cognitive load, guided by established human-centered design principles for virtual environments (Jerald, 2016). Third, through a quasi-experimental design, the study examines whether an ontology-driven, low-immersion architecture improves theoretical understanding and practical skill performance compared with conventional lecture-based instruction. Accordingly, the study tested three hypotheses: H1, students using the ontology-driven non-immersive VR system would achieve higher post-test explicit knowledge scores than students receiving conventional instruction; H2, students using the system would achieve higher practical installation skill scores; and H3, students using the system would achieve higher blueprint-reading and regulation-interpretation scores.

## 2. Theoretical framework and literature review

### 2.1. Knowledge engineering and ontologies in vocational education

Knowledge Engineering (KE) constitutes the methodological process of capturing, structuring, and representing expert human knowledge in a formalized format that can be accessed by software systems (Matkar & Parab, 2011). Within advanced vocational and technical training, KE frequently materializes through the construction of ontologies. Gruber (1993) defines an ontology as a formal, explicit specification of a shared conceptualization, while Guarino et al. (2009) further clarify the conceptual and representational role of ontologies in organizing domain knowledge. In this study, the ontology specifies concepts, properties, and relationships within the bounded domain of solar PV installation training.

Recent academic literature demonstrates the potential of ontology-based architectures in complex industrial, robotic, and safety-critical contexts. For instance, Longo et al. (2022) developed an ontology-based, Industry 4.0-ready architecture to support smart operators in mixed-reality manufacturing environments, and Cimino et al. (2024) extended this architecture to a virtual-reality case. Similarly, Manzoor et al. (2021) reviewed ontology-based knowledge representation in robotic systems and showed how physical, sequential, and procedural tasks can be represented for machine-supported reasoning. In virtual reality training, ontologies have also been discussed as a way to align training content, visual annotations, and instructional objectives across the development lifecycle (Benferdia et al., 2021; Mohamad et al., 2021). These studies suggest that ontologies can support structured learning design, although their educational value depends on transparent modeling procedures and alignment with measurable learning tasks.

### *2.2. Immersion vs. cognitive load in VR learning*

The foundation of effective multimedia instructional design within digital learning environments rests heavily on Cognitive Load Theory (CLT). Formulated by Sweller (1988), CLT posits that human working memory is severely limited in its capacity and duration, and learning is hampered if an instructional medium requires excessive mental effort merely to operate or navigate. According to the standard parameters of CLT, the total cognitive load experienced by a learner at any given moment is the sum of three distinct and interacting components: intrinsic load, extraneous load, and germane load. In the context of Virtual Reality (VR), while high immersion can foster engagement, it may also increase extraneous load by introducing complex visual and interactive elements.

While fully immersive VR setups – those using HMDs – offer high levels of spatial presence and visual fidelity, they may also impose additional extraneous load on novice users through physical discomfort, sensory overload, and the effort required to master unfamiliar controllers (Makransky et al., 2019; Radianti et al., 2020). In contrast, non-immersive VR, often referred to as desktop VR, provides a more accessible “Magic Window” experience. By reducing the operational burden associated with specialized hardware, desktop VR may allow learners to allocate more cognitive resources to schema construction and task-relevant processing (Paas & van Merriënboer, 2020; Sweller, 1988). Educational 360-degree video research further suggests that desktop and screen-based panoramic environments can provide contextual visual information while remaining technically accessible for classroom implementation (Snelson & Hsu, 2020).

### *2.3. Situated cognition and 360-degree video environments*

The theory of Situated Cognition asserts that knowledge is not a standalone artifact; rather, it is fundamentally inseparable from the context, culture, and physical environment in which it is naturally applied and developed (Brown et al., 1989). Consequently, abstracting technical, hands-on skills away from the authentic job site and into a sterile, decontextualized classroom setting severely limits a student’s ability to transfer that learning to real-world scenarios.

To facilitate situated learning digitally, 360-degree video can provide contextual visual information for learners. Unlike artificially constructed 3D computer graphics, high-definition 360-degree video captures authentic real-world environments and preserves contextual and environmental cues that technicians may rely upon (Rosendahl & Wagner, 2024). The application of 360-degree VR video has been used across high-stakes and physically demanding disciplines. For example, Babaita et al. (2024) compared 360-degree VR video with face-to-face instruction in nursing education, and Patel et al. (2020) described the development of 360-degree video for clinical trauma training. In the specific context of solar PV installation, 360-degree video can situate the learner on a sloped rooftop or within a cramped electrical room, providing contextual visual stimuli that may support spatial reasoning and hazard assessment.

### 2.4. Externalization of tacit knowledge

A central goal of the proposed ontology-driven system is to support the transfer of tacit/procedural knowledge. According to Nonaka and Takeuchi's (1995) SECI (Socialization, Externalization, Combination, Internalization) model of organizational knowledge creation, an important step in scaling expertise is the "Externalization" phase. This phase involves converting tacit expertise into explicit, visible, and communicable concepts that can be shared across an organization or classroom.

By overlaying digital, text-based ontological information directly onto a photorealistic 360-degree visual context, the proposed system creates an augmented virtuality learning environment. This environment makes selected expert cues visible for novice learners to observe and interact with. Conceptually, this design follows the externalization logic of the SECI model, in which tacit expertise is transformed into shareable explicit representations (Nonaka & Takeuchi, 1995). It also aligns with Dual Coding Theory, because learners process visual rooftop contexts and verbal ontological labels together, potentially creating multiple linked memory traces (Paivio, 1986).

## 3. Methodology and system architecture

This study was conducted in accordance with institutional ethical guidelines and was approved by the Human Research Ethics Committee. Informed consent was obtained from all participants before data collection, and participation was voluntary.

### 3.1. Knowledge ontology construction

The architectural and pedagogical foundation of the instructional system is the bespoke "Solar PV Installation Knowledge Ontology." The ontology was developed through a four-step procedure: expert elicitation, open coding of explicit and procedural knowledge units, hierarchical node-and-relation mapping, and expert validation. Certified solar PV installation experts were consulted through structured interviews, cognitive task analysis, and observation of installation procedures. The extracted knowledge elements were organized into explicit and tacit/procedural knowledge categories, reviewed by the expert panel, and mapped to corresponding VR visual cues and learning objectives. Disagreements in node classification were resolved through consensus discussion, and only knowledge elements with expert agreement were retained and mapped to VR hotspots, regulatory labels, procedural decision points, or assessment criteria. To support reproducibility, each retained knowledge element was documented with its source evidence, node label, relation type, validation decision, VR cue, learning objective, and assessment link. The resulting ontology categorizes the domain knowledge into two interconnected primary branches:

(1) *Explicit knowledge (theoretical/declarative):* This branch encompasses strictly codified, textbook-based information. It explicitly includes regulatory frameworks (e.g. National Electrical Code standards for conduit fill), mathematical electrical formulas (e.g. calculating theoretical power yields using Watt's Law, calculating string voltage limits), and precise hardware component specifications (e.g. inverter maximum capacities, micro-inverter wiring topologies, and grounding lug torque requirements).
(2) *Tacit knowledge (practical/procedural):* This branch captures the intuitive, physical realities and spatial judgments of the job site. It includes complex spatial evaluations (e.g. intuitively evaluating potential sun-shading angles across varied roof pitches at different times of day), rapid hazard identification (e.g. visually identifying compromised structural trusses or deteriorating roof membranes before stepping), and procedural physical sequencing (e.g. the ergonomic handling, lifting, and precise alignment of heavy, fragile glass PV modules on a 30-degree incline).

This formal ontology serves as the digital roadmap for the VR content ecosystem. Each interactive visual cue was mapped to a predefined learning objective, such as identifying roof-anchor placement constraints, tracing conduit routing logic, interpreting string-voltage limits, or detecting wiring-code violations (Figure 1). To make this alignment more transparent, Table 1 provides examples of how ontology nodes were connected to VR cues and assessment criteria.

**Table 1.** Ontology mapping examples used to validate node-cue-assessment alignment.

| Ontology node/relation | Knowledge type | VR cue or interaction | Learning objective | Assessment link |
|---|---|---|---|---|
| Roof-anchor placement constraints → structural integrity | Tacit/procedural | Hotspots on rooftop mounting points and warning zones around weak surfaces | Identify safe anchor positions and avoid structurally risky areas | Physical installation rubric: mounting accuracy and safety checks |
| Module handling posture → ergonomic alignment | Tacit/procedural | Ghost-hands overlay showing grip, lifting angle, and panel alignment sequence | Apply safe handling sequence before physical assembly | Physical installation rubric: ergonomic safety and mechanical accuracy |
| String voltage limit → series/parallel configuration | Explicit/declarative | Dynamic circuit overlay on PV modules and inverter connection points | Calculate and interpret safe electrical string configurations | Electrical and piping knowledge test |
| Conduit routing logic → bend radius and path planning | Tacit/procedural | Interactive tracing of conduit paths in a cramped attic environment | Select code-compliant and spatially feasible routing paths | Blueprint reading and practical routing task |
| Junction-box code violation → corrective decision | Explicit + procedural | Zoom-and-click inspection of simulated wiring errors with code-label feedback | Recognize wiring errors and connect them to regulatory rules | Blueprint/regulation interpretation and wiring inspection items |

Note: The examples show how selected ontology nodes were translated into visible VR cues and linked to learning objectives and assessment criteria; they are illustrative mappings used to document alignment rather than a complete list of all ontology elements.

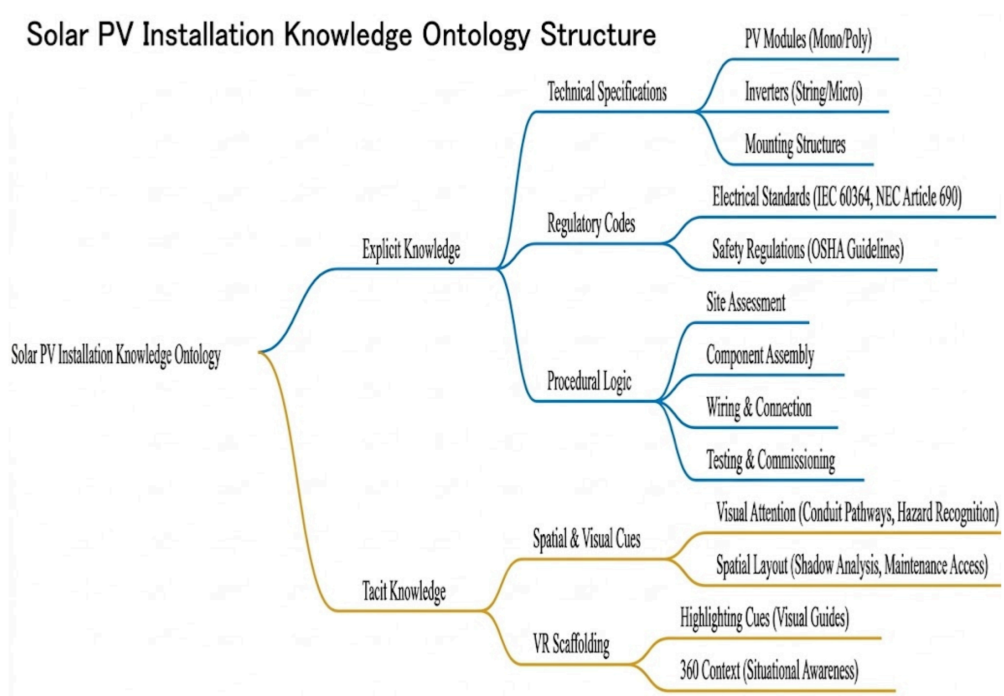


**Figure 1.** The solar PV installation knowledge ontology.

### 3.2. System architecture

The technical realization of the solar ontology was achieved through a three-tier, web-based software architecture designed for institutional accessibility and stable classroom operation (Figure 2).

(1) *Client layer (presentation):* Operating entirely within standard web browsers, this layer provides the seamless "Magic Window" interface. Users navigate the high-definition 360-degree panoramic environments using intuitive mouse drags, keyboard commands, or standard touchscreen gestures.
(2) *Application layer (logic):* These elements react based on real-time user gaze, click interactions, and progress through the module. This intermediate tier houses the "Visual Cue Engine." Driven by the underlying ontology database, this engine dynamically renders interactive hotspots, textual labels, semi-transparent safety warning zones, and dynamic electrical circuit diagrams directly superimposed onto the 360-degree video footage.

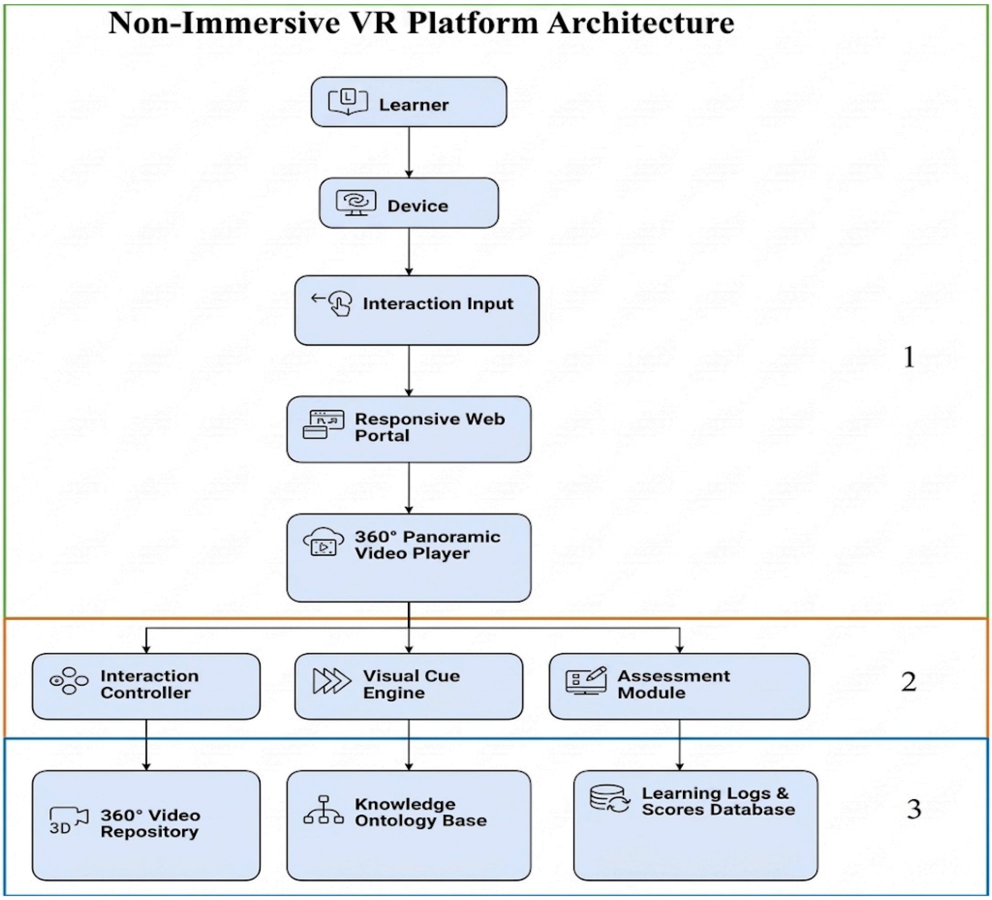


**Figure 2.** Illustrates the architecture of a non-immersive VR platform. Magic Window employs a three-layer architecture: 1. Client layer; 2. Application layer; 3. Data layer.

(3) *Data layer (storage):* This foundational tier securely archives the high-resolution 360-degree video assets, the formal XML/JSON-based ontology relationship files, and the comprehensive user interaction databases.

### *3.3. Experimental design and participants*

The participant pool comprised 65 undergraduate engineering students (61 males, 4 females; mean age = 21.4 years, SD = 1.2). The study used a quasi-experimental design with intact instructional conditions rather than individual random assignment. Prior to the intervention, a preliminary survey confirmed that none of the participants had extensive prior experience with formal virtual reality training systems in an academic setting, supporting a comparable baseline regarding technology familiarity:

- *Experimental group (n* = 33): Participants received instruction using the developed ontology-driven non-immersive VR system via desktop interfaces.
- *Control group* (n = 32): Participants received conventional vocational instruction, including PowerPoint lecture slides, whiteboard-based electrical diagrams, and static textbook review sessions.

Both groups were exposed to identical core curricular content, identical learning objectives, and identical total time-on-task. The primary instructional contrast between the two groups was the learning environment: the experimental condition integrated non-immersive VR, ontology-based visual cues, and interactive contextual scaffolding, whereas the control condition used conventional lecture-based and static materials. Therefore, the results should be interpreted as the effect of the integrated instructional environment rather than the isolated effect of a single component.

**Figure 3.** A screenshot of the photorealistic 360-degree panoramic VR instructional material filmed at the active solar PV rooftop training facility.

High-definition 360-degree panoramic video materials were captured at an authentic rooftop solar energy facility to represent expert operational sequences and contextual spatial layouts (Figure 3). During the instructional intervention, participants in the experimental group interacted with this structured media environment within a standardized computer laboratory setting using desktop interfaces, allowing collaborative scaffolding without the sensory isolation of head-mounted displays (Figure 4).

Table 2 summarizes the alignment between the 8-week instructional modules, their ontological focus, and the contrasting pedagogical activities used by each group.

### 3.4. Instruments and measurement

To evaluate the quality of the assessment tools, both reliability and content validity were examined. The explicit knowledge questionnaire demonstrated acceptable reliability (Cronbach's alpha = 0.86). Content validity was addressed through expert review: the test items, practical-skill rubric, and blueprint-reading

**Figure 4.** Engineering students engaging with the ontology-driven non-immersive VR system on desktop interfaces during the classroom learning and evaluation phase.

**Table 2.** Structure of the 8-week instructional intervention and ontology mapping.

| Week | Instructional module | Ontology focus | Traditional activity (control group) | VR activity (experimental group) |
|---|---|---|---|---|
| Wk 10 | Solar Mounting Systems | **Tacit:** Structural Integrity, Spatial Layout | Lecture slides & whiteboard demonstration of bracket spacing calculation. | **VR Visualization:** 360° tour of varied roof types; identifying hidden anchor points via interactive hotspots. |
| Wk 11 | PV Module Assembly | **Tacit:** Handling Procedures, Physical Alignment | Teacher physical demonstration followed by manual lifting practice in the lab. | **VR Simulation:** First-person view of module lifting; "Ghost hands" overlay demonstrating correct ergonomic grip and posture. |
| Wk 12 | Array Configuration | **Explicit:** Voltage/ Current String Sizing | Textbook 2D diagrams of complex series/parallel electrical circuits. | **VR Schematic Overlay:** Dynamic, glowing circuit diagrams superimposed directly onto physical panels in the 360° view. |
| Wk 13 | Conduit & Wiring | **Tacit:** Routing Logic, Bend Radius Intuition | Lab practice utilizing static, physical pipe bending tools and scrap conduit. | **VR Navigation:** Tracing optimal conduit paths in a complex, cramped 360° attic environment; actively detecting code violations. |
| Wk 14 | Junction Box Setup | **Explicit:** Code Compliance | Rote review of the codebook and static wiring manuals. | **VR Inspection:** Zooming into open, highly complex junction boxes; identifying simulated wiring errors against automated pop-up code citations. |
| Wk 15 | Troubleshooting | **Explicit + Tacit:** Diagnostic Logic | Paper-based scenario analysis and logical decision-tree worksheets. | **VR Fault Finding:** Interactive 360° environment featuring simulated, randomized system failures (e.g. invisible micro-shading, loose internal wires). |
| Wk 16 | System Commissioning | **Explicit:** Testing Protocols | Paper checklist review and rapid equipment demonstration by the instructor. | **VR Virtual Walkthrough:** Executing the start-up sequence step-by-step; visually verifying physical safety interlocks. |
| Wk 17 | Final Project | **Synthesis:** Full System Integration | Hands-on assembly exam conducted in the physical training laboratory. | VR-assisted review phase followed by the identical hands-on assembly exam in the physical training laboratory. |

tasks were checked against the ontology dimensions and course learning objectives to ensure alignment with explicit regulatory knowledge, tacit/procedural installation skills, and spatial blueprint interpretation. For the tacit/procedural practical skills assessment, a panel of three independent industry experts conducted blind ratings using a structured rubric. The inter-rater reliability among the experts indicated strong agreement (Cohen's kappa = 0.83), supporting the objectivity of the physical performance metrics:

(1) *Knowledge of electrical & piping (explicit):* Evaluated via a timed multiple-choice examination testing declarative knowledge, including electrical theory, National Electrical Code standards, and component safety specifications.
(2) *Skill of solar PV installation (tacit/procedural):* Evaluated through a highly structured, rubric-based physical performance assessment conducted in a real-world training laboratory. Blind assessors rated physical installation speed, ergonomic safety, and mechanical accuracy during a live build.
(3) *Cognitive ability in blueprint reading (spatial/contextual):* Evaluated via a specialized spatial reasoning test requiring participants to accurately convert flat, traditional 2D electrical schematics into viable, safe, and efficient 3D physical layout plans.

**Table 3.** Differences in outcome variables within and between the intervention and control groups.

| Variables | T0 mean | T0 SD | T1 mean | T1 SD | T1–T0 mean gain | Between-group *t*-test at T1 | Cohen's d |
|---|---|---|---|---|---|---|---|
| *Knowledge of Electrical and Piping Installation* | | | | | | | |
| Intervention Group | **3.36** | **0.89** | **7.43** | **0.50** | **4.07** | **3.88 ($p < .001$)** | **0.96** |
| Control Group | **3.37** | **0.97** | **6.03** | **2.01** | **2.66** | | |
| *Skill of Solar Energy System Installation* | | | | | | | |
| Intervention Group | **4.13** | **0.86** | **7.50** | **0.57** | **3.37** | **4.21 ($p < .001$)** | **1.04** |
| Control Group | **3.94** | **0.80** | **6.80** | **0.76** | **2.86** | | |
| *Blueprint Reading and Regulations* | | | | | | | |
| Intervention Group | **3.60** | **0.77** | **7.53** | **0.73** | **3.93** | **4.41 ($p < .001$)** | **1.09** |
| Control Group | **3.40** | **0.74** | **6.63** | **0.91** | **3.23** | | |

Note. T0 = pre-test; T1 = post-test. Intervention group $n$ = 33; Control group $n$ = 32. The $t$-values represent the between-group differences at T1. Cohen's $d$ was calculated using the pooled standard deviation. Effect sizes were interpreted according to Cohen's conventional benchmarks (Cohen, 1988). Holm-Bonferroni adjustment was applied across the three primary T1 between-group comparisons; all adjusted comparisons remained significant at $p < .001$.

## 4. Empirical results and system validation

### 4.1. Empirical results and system validation

The quantitative data collected from the pre- and post-intervention assessments were analyzed using independent-samples *t*-tests for the primary between-group T1 comparisons. Baseline comparisons indicated no statistically significant differences between the experimental and control groups across the three pre-test measures: Knowledge of Electrical and Piping Installation, $t(63) = -0.04$, $p = .966$; Skill of Solar PV Installation, $t(63) = 0.92$, $p = .360$; and Blueprint Reading and Regulations, $t(63) = 1.07$, $p = .290$. These results suggest that the two groups were comparable at baseline for the measured outcomes. Accordingly, the post-test between-group comparisons were retained as the primary outcome analyses. Because three primary T1 comparisons were conducted, Holm-Bonferroni adjustment was applied; all three post-test comparisons remained statistically significant after adjustment. The findings are interpreted cautiously in light of the quasi-experimental design and sample size.

### 4.2. Analysis of explicit knowledge acquisition

The acquisition and retention of explicit declarative knowledge forms the core baseline of regulatory compliance and fundamental safety in electrical trades. As shown in Table 3, the experimental group achieved a larger gain in Knowledge of Electrical and Piping Installation than the control group. At T1, the experimental group scored significantly higher than the control group, $t(63) = 3.88$, $p < .001$, Cohen's $d = 0.96$, 95% CI for the mean difference [0.68, 2.12]. The mean gain was 4.07 points in the experimental group and 2.66 points in the control group, indicating a larger pre-post improvement in explicit knowledge among students who received the ontology-driven non-immersive VR intervention.

Furthermore, when evaluating final learning outcomes, the experimental group achieved approximately 23% higher post-test scores than the control group ((7.43 −6.03)/6.03 = 23.2%). This difference suggests that the Visual Cue Engine may have helped anchor abstract theoretical information to concrete visual examples within the 360-degree environment. By viewing regulatory text alongside the physical junction box to which it applied, learners encountered a design consistent with Dual Coding Theory (Paivio, 1986).

### 4.3. Analysis of practical skill transfer

For Skill of Solar PV Installation, the experimental group also demonstrated higher post-test performance than the control group, $t(63) = 4.21$, $p < .001$, Cohen's $d = 1.04$, 95% CI for the mean difference [0.37, 1.03]. It is important to contextualize this result: the non-immersive VR system used by the experimental group relied on standard mouse and keyboard inputs and did not provide actual physical or haptic manipulation of tools, brackets, or glass materials. Therefore, the improvement in physical lab performance by the VR group should be interpreted as evidence of improved cognitive blueprinting and procedural preparation rather than definitive proof of complete tacit knowledge transfer.

By virtually rehearsing the installation sequences repeatedly, observing correct spatial routing from expert vantage points, and interacting with the "ghost hands" ergonomic overlays, students appeared to develop a more organized internal representation of the physical task. Quantitatively, this resulted in the Experimental Group achieving approximately 10% higher final practical skill performance scores than the Control Group ((7.50 −6.80)/6.80 = 10.3%). This finding suggests that ontology-driven visual scaffolding and contextualized 360-degree practice may support the transfer of procedural and spatial aspects of vocational skills from virtual rehearsal to physical task performance.

### 4.4. Analysis of cognitive blueprint reading

The cognitive ability to translate flat, abstracted 2D documentation into three-dimensional physical arrangements is a distinct feature of technical expertise in construction and engineering trades. For Blueprint Reading and Regulations, the experimental group significantly outperformed the control group at T1, $t(63) = 4.41$, $p < .001$, Cohen's $d = 1.09$, 95% CI for the mean difference [0.49, 1.31]. This result is consistent with situated cognition, suggesting that learning schematic symbols within contextualized 3D environments may support spatial-cognitive translation.

## 5. Discussion

### 5.1. The role of "magic window"interaction in cognitive load management

The empirical results generated by this study contribute to the ongoing academic discussion regarding appropriate immersion levels in educational technology. The data show that the non-immersive, desktop-based VR approach was associated with improved performance in this solar PV vocational training context. By intentionally using a simple Magic Window interface, the system was designed to reduce technology-related instructional barriers that may contribute to extraneous cognitive load. However, because cognitive load was not directly measured, this interpretation should be regarded as a theory-informed explanation rather than direct psychometric evidence. Compared with fully immersive stereoscopic HMDs, which can introduce sensory and navigational demands for novices, the desktop interface provided an accessible conduit for task-relevant information (Makransky et al., 2019; Radianti et al., 2020).

This interpretation is consistent with Makransky et al. (2019), who found that high-immersion environments can increase presence while reducing learning under some conditions. Because the desktop interface relied on familiar mouse and keyboard operations, it may have reduced operational demands and allowed learners to focus more attention on electrical logic and spatial relationships within the solar installation task. This design rationale is also consistent with Cognitive Load Theory, which emphasizes reducing extraneous processing so that learners can devote more working-memory resources to schema construction (Paas & van Merriënboer, 2020; Sweller, 1988). The higher final academic and physical performance outcomes therefore serve as behavioral indicators that are compatible with this explanation, rather than direct measures of mental workload.

### 5.2. Externalizing tacit knowledge through visual scaffolding

A primary contribution of the proposed VR architecture is its attempt to make selected expert cues visible. Expert solar installers do not merely look at a roof; they interpret a matrix of subtle visual cues regarding structural load distribution and sun trajectories. By cataloging these cues within the KE ontology and rendering them as interactive visual scaffolds within the 360-degree environment, the system externalized parts of experts' tacit mental models for novice learners. The statistically significant gain in physical skills suggests that students may have internalized some of these highlighted cues and retrieved them during real-world construction tasks (Nonaka & Takeuchi, 1995; Paivio, 1986).

The following conceptual model is presented as a heuristic explanation rather than a mathematical equation derived from the empirical data. In this model, tacit/procedural learning is supported when the level of immersion is sufficient to preserve spatial context, but not so high that the interface itself becomes a major source of extraneous load.

$$K_{learner} = f(K_{expert} \times I_{VR} \times O_{mapping})$$

In this theoretical model, $I_{VR}$ represents the optimal immersion factor (the balance between psychological presence and cognitive load), and $O_{mapping}$ represents the exact precision of the ontological alignment between the digital curriculum cues and the physical task. The proposed system maximized $O_{mapping}$ by ensuring every single interactive element was tied directly to a formal, examinable curriculum objective. The model assumes that each interactive cue should correspond to a defined learning objective, assessment criterion, or procedural decision point. In the present system, the ontology was used to link visual hotspots, regulatory labels, and installation procedures to examinable curricular objectives.

### 5.3. The Cognitive Mechanics of Interactivity in the "Magic Window"

While the visual externalization of tacit knowledge is important, the pedagogical value also lies in the system's interactive mechanisms. The experimental group's higher practical skill performance (Table 3) cannot be attributed solely to passive viewing of a 360-degree environment. Instead, learner-driven interaction with ontological overlays may have supported deeper processing by prompting students to select, compare, and verify task-relevant cues (Paas & van Merriënboer, 2020; Sweller, 1988).

The Magic Window environment encouraged active cognitive engagement through specific interactive behaviors. For instance, in the Junction Box Setup module (Week 14), learners did not simply view a correct wiring diagram; they zoomed in, clicked to inspect specific terminals, and made decisions that triggered ontologically mapped code citations. This action-feedback loop positioned the learner as an active problem-solver. These interactions served as external cognitive scaffolds that may have helped learners construct and refine mental schemas linking declarative rules with physical actions.

### 5.4. Scalability, Industry 4.0, and system architecture implications

From a system-design and institutional perspective, this research illustrates the potential utility of ontology-driven architecture for organizing vocational learning content and linking it to interactive visual scaffolds. By separating the Knowledge Model from the Presentation Layer, the study presents a modular software architecture that may be useful for vocational training in rapidly evolving fields such as renewable energy. When codes are updated or new hardware is released, developers can update the underlying ontology database and reuse existing 360-degree visual assets where appropriate. This modularity is consistent with Industry 4.0 discussions of knowledge-supported smart-operator systems in mixed-reality and virtual-reality manufacturing contexts (Cimino et al., 2024; Longo et al., 2022). Furthermore, the system's web-based deployment may broaden access to technical training without requiring high-end VR headsets.

### 5.5. Limitations and future research

While this study provides preliminary empirical evidence for the potential of ontology-driven non-immersive VR in solar PV vocational training, several limitations must be acknowledged. First, the sample size was relatively small ($N$ = 65), and the participants were recruited from a single solar-related engineering course at one technical institution. Consequently, caution should be exercised when generalizing these findings to other vocational fields, institutions, or industrial training contexts.

Second, this study did not employ direct psychometric scales, such as the NASA Task Load Index (Hart & Staveland, 1988), or physiological metrics, such as eye-tracking or electroencephalography, to empirically quantify learners' cognitive load during active navigation. The cognitive load management benefits of the Magic Window interface were inferred primarily through objective behavioral outputs and final skill acquisition performance. Third, the study included only immediate post-tests and did not examine delayed retention, long-term transfer, or contextual application in workplace settings. Future research should incorporate standardized cognitive-load measures, delayed post-tests, and longitudinal transfer assessments to cross-validate how ontology-driven visual scaffolds affect working memory demands and durable vocational skill acquisition.

## 6. Conclusion and future directions

### 6.1. Summary of findings

This study provides evidence that an ontology-driven, non-immersive VR environment may scaffold vocational learning by converting selected expert cues into structured, interactive 360-degree activities. In the quasi-experimental comparison, students using the desktop-based Magic Window system achieved significantly higher post-test performance in explicit knowledge, practical installation skills, and blueprint/regulation interpretation than students receiving conventional instruction. These findings reinforce the central thesis: in vocational VR, educational value depends less on maximizing immersion than on aligning domain knowledge, contextual visual cues, learner interaction, and assessment within an accessible instructional environment. Because cognitive load was not directly measured, the proposed accessibility benefit of the desktop interface remains a theory-informed explanation rather than direct psychometric evidence.

The study contributes theoretically by connecting Knowledge Engineering with situated cognition, dual coding, and cognitive-load-informed multimedia design, and practically by presenting a scalable, web-based architecture for high-risk green-energy training. Future research should replicate the findings across institutions and vocational domains, incorporate direct cognitive-load measures and delayed-transfer assessments, and evaluate transparent AI-supported knowledge graphs that adapt scaffold timing and density while retaining expert validation.

## Author contributions

**Chun-Chin Tsai:** Conceptualization, Methodology, Software, Validation, Visualization, Writing – original draft and Editing.
**Mei-Fang Chen:** Validation

## Disclosure statement

No potential conflict of interest was reported by the author(s).

## AI-assisted language editing statement

During the revision process, the authors used generative AI tools only for language polishing, formatting support, and editorial organization. The authors independently verified all scholarly content, references, data analyses, interpretations, and conclusions, and take full responsibility for the final manuscript.

## Ethics statement

This study was conducted in accordance with institutional guidelines and was formally approved by the Human Research Ethics Committee. Informed consent was obtained from all individual participants included in the study. All participants were informed about the study's purpose, voluntary nature of participation, and their right to withdraw at any time without any academic penalty.

## Informed consent

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## Data availability statement

The datasets generated and analyzed during the current study are not publicly available due to strict institutional ethical restrictions regarding student privacy and academic records, but fully anonymized data subsets are available from the corresponding author upon reasonable request.

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