



Article

Utilizing VR Technology in Foundational Welding Skill Development

Nuri Furkan Koçak ^{1,*} , Ali Saygın ² and Fuat Türk ³ ¹ Department of Electrical and Electronics Engineering, Graduate School of Natural and Applied Sciences, Gazi University, Ankara 06500, Türkiye² Department of Electrical and Electronics Engineering, Faculty of Technology, Gazi University, Ankara 06500, Türkiye; asaygin@gazi.edu.tr³ Department of Computer Engineering, Faculty of Technology, Gazi University, Ankara 06500, Türkiye; turkfuat@gazi.edu.tr

* Correspondence: nfurkan.kocak@gazi.edu.tr

Abstract

Traditional approaches to welder training demand substantial investments in equipment, consumable materials, and workshop facilities, while also exposing novice learners to considerable safety risks. This study investigates the effectiveness of a virtual reality (VR)-based welding training system developed with Unity for the Meta Quest 2 platform, designed to deliver safe and immersive instruction in fundamental welding techniques. A total of twenty participants with no prior welding experience completed structured VR training sessions over two weeks. The program focused on developing competencies in welding machine operation (including start-up procedures and parameter adjustments), controlling shielding gas flow, and accurately regulating torch-to-workpiece distance, torch angle, and travel speed. Real-time feedback was integrated into the system to support accurate control and positioning of the welding torch. Quantitative assessments demonstrated significant improvements in both technical proficiency and trainee confidence and anxiety levels. Knowledge test scores increased from 45.3 to 85.1, while machine adjustment accuracy rose from 28.7 to 92.3. In parallel, participant confidence levels increased substantially, and anxiety scores decreased from 4.0–4.5 to 1.1–1.5 on standardized scales. These findings provide experimental evidence that VR-based training can enhance fundamental welding education by offering a safe, repeatable, and effective practice environment that simultaneously improves technical performance, strengthens learner confidence, and reduces training-related anxiety.

Keywords: virtual reality (VR); welding training; MIG/MAG welding; real-time feedback; Unity; Meta Quest



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1. Introduction

Welding is a critical skill underpinning industries ranging from manufacturing to energy, yet the welding training required to produce competent operators is intensive, hazardous, and logistically challenging [1]. Welding education requires not only theoretical knowledge but also a high degree of attention, fine motor skills and precise hand-eye coordination. Traditionally delivered through in-person, workshop-based training, welding instruction often faces significant limitations, including high costs of consumables and equipment, safety hazards, and limited student–instructor interaction [1].

In response to these challenges, virtual reality (VR) training simulators have emerged as an innovative alternative in vocational and technical education [2]. VR systems allow users to handle virtual welding torches within immersive environments, where important welding parameters, such as the angle of the torch, the travel speed and the distance to the workpiece, can be instantly modified during simulation [3]. Recent developments further extend these capabilities to include adjustments of wire feed speed and shielding gas flow, mirroring the operation of authentic equipment. At the same time, multimodal feedback (visual, auditory, and haptic) supports immediate error correction [4]. Notably, VR learning environments embody the principles of constructivist and experiential learning theories, allowing trainees to build knowledge through hands-on interaction rather than passive observation, and aligning with adult learning principles such as self-direction, problem-centeredness, and relevance to real-world contexts [5].

Beyond welding, VR training has demonstrated robust pedagogical value across diverse domains. In healthcare, meta-analyses confirm significant improvements in knowledge and psychomotor skills, as well as reduced procedural time, when using immersive VR simulations [6]. In construction, VR-based safety training enhances hazard recognition and reduces on-site accidents [7], while in aviation, immersive scenarios prepare trainees for emergency maneuvers and monitor stress regulation [8]. Extended reality (XR) applications have also shown strong positive effects in language learning, with a meta-analysis reporting an effect size of 0.825 [9]. These findings highlight the dual impact of VR: it enhances technical skill acquisition while also influencing motivational, emotional, and interpersonal outcomes.

The evidence from welding-focused research has also been encouraging. A portable VR welding training system developed using commercial headsets and 3D-printed torches for MIG/MAG processes achieved high levels of user satisfaction and perceived usability [10]. Similarly, VR-enhanced programs have been shown to improve torch control, increase soldering speed, and reduce learners' anxiety [11,12]. These outcomes align with broader findings in adult education, where VR fosters motivation, engagement, and self-efficacy—critical affective components often overlooked in traditional welding instruction [13]. Meta-analyses further confirm that VR yields comparable or superior outcomes to traditional training, particularly in repetitive, skill-based tasks [14,15].

Nevertheless, results remain mixed. While VR consistently improves procedural accuracy and learner confidence, cognitive benefits such as critical thinking and long-term knowledge retention show less consistent improvement [16]. Moreover, affective dimensions—including anxiety regulation, empathy, and cross-cultural learning—remain underexplored in welding-specific studies [17]. This underscores the need for research that integrates both technical and psychological perspectives.

The present work addresses this gap by implementing a VR training program developed in Unity and deployed on Meta Quest 2 VR headset (Meta Platforms, Menlo Park, CA, USA). The program targeted individuals with no prior welding experience. It evaluated pre- and post-training changes in welding knowledge, the ability to operate and adjust the welding machine and regulate gas flow, the ability to control the angle of the torch and the extension of the electrode, the self-confidence in welding skills and anxiety related to the welding environment.

By combining subjective (confidence, anxiety, motivation) and objective (technical accuracy, machine handling) measures, this study contributes not only to the evidence base of VR in welding education but also to the broader discourse on how VR supports lifelong learning, skill democratization, and adult education. Unlike prior studies that primarily focused on procedural outcomes, this work explicitly integrates both technical and affective

dimensions, thereby offering a more holistic evaluation of VR-based welding education and clarifying its pedagogical novelty.

2. Literature Review

VR technologies have a practical application in the field of vocational education by connecting theory to practice. VR increases the effectiveness and safety of training processes in various industries. In design education, particularly within architecture and interior architecture, VR applications are shown to enrich the learning experience by contributing to the development of spatial perception and design processes, often compared with 3D printing for complex architectural geometries [18].

In the field of healthcare, VR facilitates the instruction of complex procedures such as dialysis treatment and surgical operations in a risk-free environment. Immersive medical scenarios have both safety benefits and enhance team communication [19,20]. The training of endotracheal intubation and the care of dialysis using virtual reality has been demonstrated to abbreviate the learning curve and reduce the frequency of error [21,22].

In industrial and manufacturing settings, VR simplifies the teaching of technical operations such as assembly, maintenance, and CNC machining. Learners can engage with high-risk, high-cost tasks without real-world consequences. Research shows that VR-based training improves knowledge retention and enhances productivity [23–25]. For example, simulations that focus on CNC grinding machines help users comprehend the technical procedures involved in detail, which increases the user's retention of the information [26]. To further enhance efficiency in industrial and manufacturing settings, digital solutions such as the Model Based Definition (MBD) enhanced Asset Administration Shell (AAS) are being developed for the design of generic production lines, addressing challenges of rapid reconfiguration and interoperability [27].

The construction industry—known for its hazardous work environments—has also integrated VR into its training systems. Trainees can explore virtual construction sites and engage in safety protocols in simulated high-risk conditions. Compared to traditional video-based instruction, VR promotes the recognition of hazards and the awareness of emotional consequences of workplace risks [7,28].

In the aerospace and aviation industries, VR allows pilots and other technical personnel to repeatedly learn about pre-flight procedures, engine failures, and emergency maneuvers. These immersive environments can be altered through neurotechnology to assess the attention and stress levels of individuals, which will allow for more individualized experiences in training [8,29]. Also, VR has been utilized to enhance the accuracy and efficiency of the aircraft component assembling process [30].

Welding education is confronted with obstacles like high costs of equipment, safety concerns, and a limited number of practical applications, which are addressed by simulators that use head-mounted displays and control devices to provide realistic environments. These systems offer immediate feedback, which allows learners to assess their progress immediately via virtual or physical means, respectively [4,14]. Advanced simulations track technical parameters like seam geometry and porosity, making the learning process more tangible [11]. Applications of virtual reality in vocational education across sectors are summarized in Table 1.

Significantly, these systems not only improve technical competencies—they also boost learners' self-confidence and reduce performance anxiety [12]. Demonstrated that VR-based instruction produced performance outcomes statistically comparable to traditional methods, confirming its pedagogical reliability [15]. Furthermore, the repeatability, reduced equipment dependency, and integration with remote learning make VR an excellent fit for Industry 4.0 and 5.0 training needs [11].

Table 1. Applications of virtual reality in vocational education across sectors.

Sector	Application	Citation
Healthcare	Dialysis training, endotracheal intubation, surgical simulation	[19–22]
Manufacturing	CNC machine operation, maintenance procedures, technical skill acquisition	[23–26]
Construction	Site safety training, hazard recognition, virtual walkthroughs of construction environments	[7,28]
Aviation/Aerospace	Pre-flight checks, emergency response training, component assembly, attention-stress monitoring	[8,29,30]
Welding	Virtual welding practice, seam geometry tracking, real-time feedback on technique and safety	[4,11,14]
General Vocational Training	Confidence building, repeatable simulation environments, integration into remote education	[11,12,15]

While prior studies have primarily emphasized procedural accuracy and technical performance in VR-based welding training, relatively little attention has been given to integrating real-time multimodal feedback with the systematic evaluation of affective outcomes, such as trainee confidence and anxiety reduction. This gap limits our understanding of how VR training environments influence both technical skill acquisition and psychological factors that are critical for effective learning. The present study addresses this gap by explicitly combining objective technical assessments with validated confidence and anxiety scales, thereby offering a more holistic evaluation of VR-based welding education and demonstrating how immersive VR can simultaneously enhance procedural accuracy, strengthen learner confidence, and reduce training-related anxiety.

3. Materials and Methods

3.1. Hardware Infrastructure

The quality of a VR experience is directly dependent on the accuracy and realism of visual, auditory, and tactile stimuli in the user's environment. The key hardware components in this study include the Meta Quest 2 headset with integrated sensors and a high-quality audio system, as well as standard handheld controllers, as illustrated in Figure 1.

**Figure 1.** Meta Quest 2 headset and controllers were used in the study.

Standalone Head-Mounted Displays (HMDs) such as the Meta Quest 2 eliminate the need for an external computer, offering revolutionary flexibility in educational settings through their wireless design and rapid setup. These devices can be easily integrated into classrooms or workshops and serve many users at a low cost [11]. They provide stereoscopic 3D viewing, improving depth perception through high-resolution displays [31,32]. The integrated sensors of the device detect the head, hand and body movements of the user in a 3D space, tracking their position and orientation in real time, and updating the virtual scene accordingly [32,33]. High-quality audio systems significantly enhance the sense of immersion by providing realistic and spatial sound; these systems convey sounds and feedback alerts to the user [32]. The ongoing evolution of hardware continues to be a driving force in the development of VR technology [34].

3.2. Software Infrastructure

The efficacy of VR simulations is primarily based on the software infrastructure that is essential for creating, rendering, and managing interactions between users and environments within simulators. In this work, the Unity game engine (version 2022.3.62f2) was chosen because of its large developer community, large asset store, and integrated nature with the VR Software Development Kit (SDK), as demonstrated in Figure 2. Unity is a game engine and an integrated development environment (IDE) designed for the development of interactive media, primarily video games [35]. These attributes make it a popular choice for educational purposes and rapid prototyping.

In the context of welding training, Unity allowed the analysis of key parameters such as electrode angle, distance and speed, while providing real-time visual, auditory, and haptic feedback to the user [3]. Additionally, the data obtained through cloud-based remote systems allows instructors to observe student performance and create individualized training programs that are [10]. Such feedback can be delivered within seconds, faster and more consistently than manual instructor observations.

Although direct latency measurements were not conducted in this study, prior research provides reference values for contemporary head-mounted displays, including Quest-class devices. Motion-to-photon latencies ranging from 21 to 42 ms have been reported for widely used PC-based HMDs, with effective delays further reduced during sustained motion through the use of prediction algorithms [36]. A methodological evaluation of the Meta Quest 2 hand-tracking system identified a mean temporal delay of approximately 38 ms, confirming that Quest-class devices operate within the low tens of milliseconds range [37]. To provide empirical validation of our specific implementation, subsequent technical analysis using the Meta Quest Developer Hub performance profiling tool confirmed that the maximum delay observed in our integrated hardware–software configuration was 14.07 ms.

Collectively, these findings suggest that the latency performance of the hardware–software configuration employed in this study lies within the thresholds generally regarded as acceptable for real-time training applications.

This measured maximum delay of 14.07 ms, along with the prior cited latency values (21–42 ms for PC-based HMDs and ≈ 38 ms for Quest-class devices), is well below the 20 ms threshold commonly regarded as acceptable for real-time training applications in immersive education. This low motion-to-photon latency (14.07 ms), combined with the device's precise spatial tracking capability, constitutes a core design implementation aimed at mitigating VR-induced simulator sickness (motion sickness) during the extended two-week training sessions. Maintaining latency below the 20 ms threshold is crucial, as visual-vestibular mismatch caused by poor tracking or high delay is a known trigger

for discomfort in VR environments. Therefore, the Meta Quest 2 platform provides a technically suitable basis for delivering VR-based welding training without perceptible delays that might disrupt learning, ensuring the high tracking accuracy necessary for real-time feedback on complex welding parameters (e.g., precise torch angle and travel speed control). Importantly, during the live observation of the VR session—transmitted to an external monitor or projector—no noticeable latency was detected. This real-time transmission capability is essential for instructors to conduct immediate, simultaneous monitoring of the user’s performance, further confirming the robust real-time operational status of the developed system.

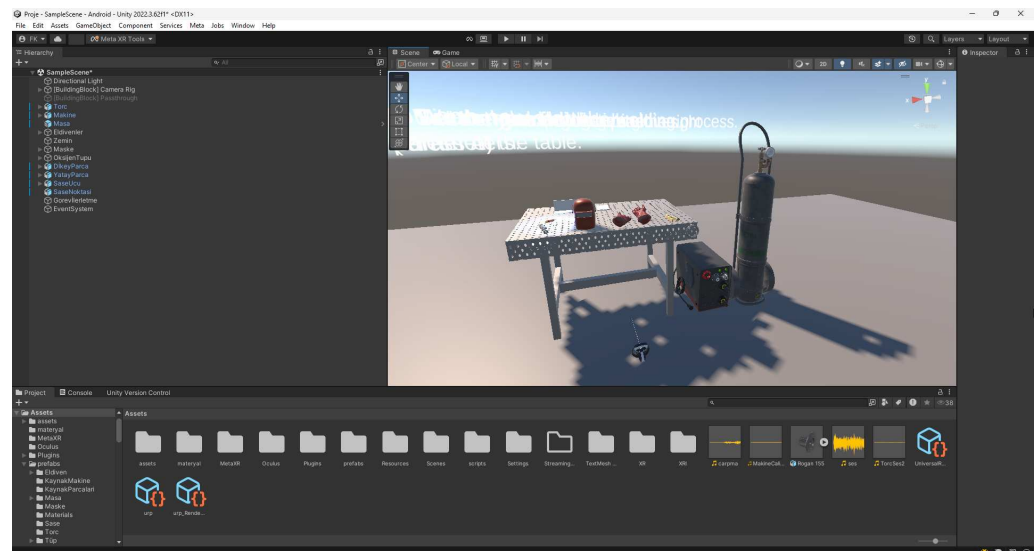


Figure 2. Structure of the VR welding environment developed in Unity.

3.3. Gas Metal Arc Welding (GMAW-MIG/MAG) Simulation Design

Gas Metal Arc Welding (GMAW), also known as Metal Inert Gas (MIG) or Metal Active Gas (MAG) welding, is a semi-automatic or automatic welding process that uses a continuously fed consumable wire electrode [38]. This method is widely applied in automotive manufacturing, general fabrication, and mass production environments [39]. GMAW’s multiple benefits include high rates of deposit, Constant operation ability, flexibility in various positions of welding, and compatibility with various materials [39]. However, it also has limitations, such as relatively high equipment costs, susceptibility to wind interference in outdoor applications (which can disperse the shielding gas), and the risk of distortion when welding thin materials [40].

The GMAW system consists of several key components: a power source, wire feeder unit, welding torch, shielding gas cylinder, and regulator [40]. The interface design of the virtual welding simulator was modeled after the Magmaweld RS300 MK machine to ensure realism and practical relevance.

Before any welding can take place in the developed VR simulation, there is a short checklist to get through—each step done in a set order. It is a way to keep the learning process consistent and to make sure safe working habits stick. The order of these actions is as follows: (1) attach the ground clamp to the upper right corner of the welding table; (2) specify the thickness of the workpiece and adjust the machine parameters accordingly; (3) adjust the shielding gas flow; (4) start the welder by pressing the designated ‘A’ button; (5) put on protective gloves; (6) put on a welding helmet; and finally (7) start the welding process. As shown in Figure 3a, the application arranges the required steps sequentially on the display. Completion of any given step changes its title to green (Figure 3b) and automatically initiates the next stage. Through this visual progression system, participants

can follow their development and complete the training in a clearly defined sequence. The implementation of these sequential steps serves to reinforce occupational safety habits and maintain the pedagogical coherence of the training program.

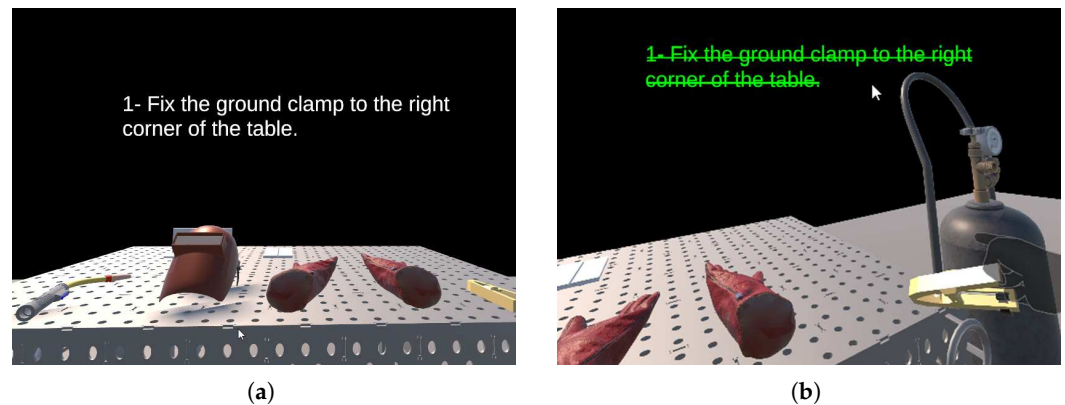


Figure 3. (a) Actual screen capture displaying the sequential procedural steps on the application screen. (b) Actual screen capture showing a completed step highlighted in green.

When the application starts, the user is first asked to secure the grounding clamp to the right corner of the welding workbench. As shown in Figure 3a, the user is guided to attach the grounding clamp correctly. The ground clamp must be properly connected as a key step in the welding procedure. This connection allows the current to pass through the workpiece correctly and supports compliance with standard safety protocols in conventional welding.

In the second step, the user is asked to specify the thickness of the workpiece to be machined and to set the machine parameters. When the user moves their hand close to the machine adjustment knob, the system detects this interaction and opens a digital control panel screen. The user is first required to select the thickness of the material to be welded, as illustrated in Figure 4a. Subsequently, the user is expected to adjust the coarse setting, the fine setting, and the wire feed speed parameters in sequence, as shown in Figure 4b. At this stage, the system considers the wire diameter of the welding machine to be 1 mm. To allow the user to configure the technical settings correctly, a welding parameter setting table is presented when the “Help” button is pressed, as shown in Table 2. This reference chart indicates appropriate voltage and current values based on material thickness and wire diameter, enabling the user to make informed parameter selections [40]. If the user enters an incorrect setting, the system displays a “Warning! Check voltage setting” message on the screen and prompts the user to make the necessary correction. When all parameters are set correctly, the user completes this step by pressing the “Okay” button.

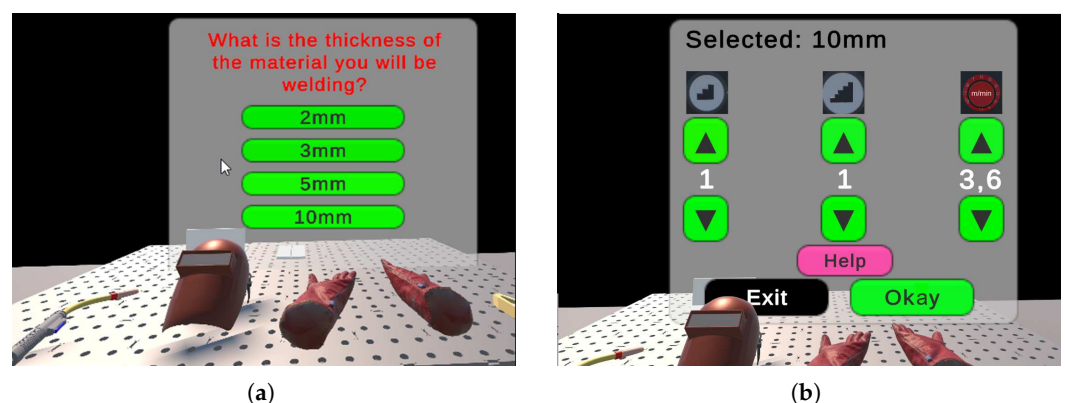


Figure 4. (a) Actual screen capture illustrating the material thickness selection interface. (b) Actual screen capture showing the digital control panel for wire feed speed, coarse, and fine parameter adjustments.

Table 2. Welding parameter settings for 1.0 mm wire diameter using CO₂ and Ar/CO₂ (80/20) shielding gases [41].

Material Thickness (mm)	CO ₂				Ar/CO ₂ (80/20)				
	2	3	5	10	2	3	5	5	10
Coarse Adjustment Range	1	1	2	3	1	1	2	3	3
Fine Adjustment	3	5	2	2	2	5	6	2	6
Wire Feeding Speed	3.2	3.8	6.3	11.2	4.5	6.3	9.3	11.1	19.2
Current (A)	100	110	150	210	120	150	200	230	300
Voltage (V)	18	19	21	28	17	18	24	28	34

In the third step, the user is asked to adjust the protective gas flow. The user directs their hand to the adjustment valve on the tube to adjust the protective gas flow rate. As shown in Figure 5a, a panel opens on the screen and the user is asked to select the wire diameter used in the welding machine. The user is instructed to set the flow rate in liters per minute (L/min) [40]. The appropriate shielding gas flow rate (CO₂, Ar, or gas mixtures) corresponding to the selected wire diameter is determined concerning Table 3. It is then adjusted as shown in Figure 5b. If the gas flow rate is not set within the recommended range, the system provides immediate feedback to the user. In this case, the following warning message is displayed on the screen: “Warning! Check the correct gas flow.” Insufficient gas flow can cause porosity, while excessive flow leads to unnecessary gas consumption [40].

In the fourth step, the user is asked to start the welding machine. The user must place their hand on the welder’s power button and press the “A” button to start the machine. In the fifth step, before starting the welding process, the user is asked to put on protective gloves, as shown in Figure 6a. Then, in the sixth step, the user is instructed to use the controller to place the welding helmet on their head, as shown in Figure 6b. The system restricts the start of the welding process until both safety measures are complete, reinforcing the proper safety procedures through experiential learning. Through these formal steps of interaction, users are allowed not only to develop their technical abilities but also to learn about occupational health and safety. When all these preparations are completed, the system allows the user to start the welding process.

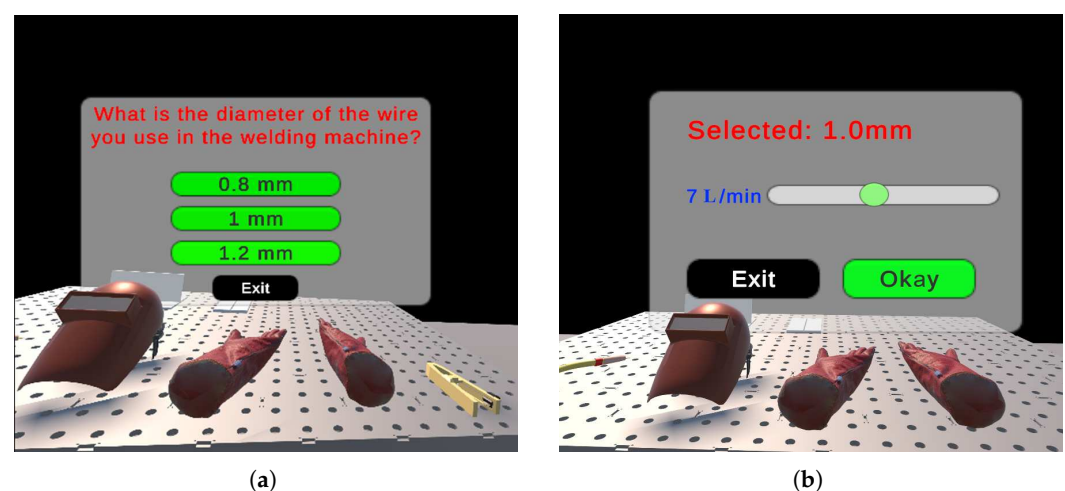
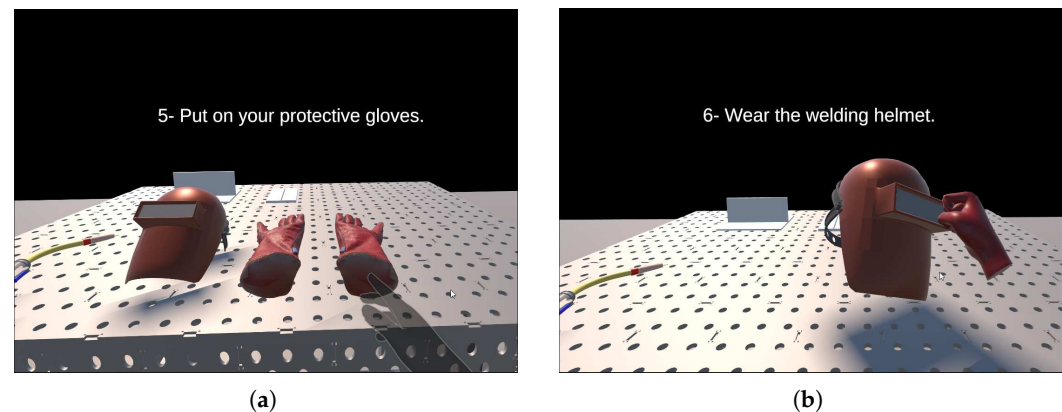
**Figure 5.** (a) Actual screen capture of the interface for wire diameter selection. (b) Actual screen capture illustrating the shielding gas flow adjustment interface.

Table 3. Recommended shielding gas flow rates by wire diameter and material type [41].

Diameter (mm)	Mild Steel and Metal Cored	Flux Cored	Stainless Steel	Aluminium
0.8	8 L/min	7 L/min	8 L/min	8 L/min
0.9	9 L/min	8 L/min	9 L/min	9 L/min
1.0	10 L/min	9 L/min	10 L/min	10 L/min
1.2	12 L/min	11 L/min	12 L/min	12 L/min
1.6	16 L/min	15 L/min	16 L/min	16 L/min

**Figure 6.** (a) Actual screen capture showing the user performing the mandatory safety step of wearing protective gloves. (b) Actual screen capture illustrating the user attaching the welding mask to the head using the controller.

To ensure the reliability and validity of the evaluation instruments, the knowledge assessment was developed in consultation with two faculty members specializing in welding education. The test consisted of 20 multiple-choice items that addressed the fundamental principles of GMAW, including safety procedures, parameter configuration, and equipment operation. Each correct response was assigned a value of five points, resulting in a maximum possible score of 100. In addition, machine adjustment tasks were evaluated using a standardized rubric derived from established welding parameter guidelines [41]. The rubric measured the accuracy of voltage, current, wire feed speed, and shielding gas adjustments, with partial credit allocated for parameter settings that fall within acceptable tolerance ranges.

Several things can affect weld quality. Torch angle, welding speed, and the length of the electrode extension are among the most important [42]. Out of these, the torch angle seems to matter the most. It not only changes how deep the weld goes, but also the shape of the weld pool [40]. Previous research and welding standards indicate that keeping the angle between 0° (perpendicular) and 15° usually provides good penetration and leads to a better bead appearance, whereas angles beyond 20° significantly reduce penetration [43–45]. In the current work, participants were therefore instructed to keep the torch within the 0°–15° range. If the angle went beyond the allowed range, a warning appeared on the screen stating “Please correct the torch angle!!!” and it disappeared automatically once the user adjusted the torch back to the proper position. This procedure enables users to develop the skill of maintaining the torch at the correct angle.

Electrode extension (stick-out) is the distance between the contact tip and the end of the welding wire. Increasing this distance increases electrical resistance, leading to increased preheating of the wire. Although an excessive electrode extension increases resistance and deposition, it reduces arc heat, resulting in shallow penetration and a steep crowned weld bead. An insufficient electrode extension limits preheating and can impair weld quality [46].

Variations in the length of the electrode extension, particularly in semi-automatic welding processes due to manual torch manipulation, lead to current fluctuations that adversely affect weld quality and process consistency [47].

Participants were guided to keep the electrode extension distance above 5 mm. Whenever the distance dropped below this value, a warning message—“Pull the torch back!!!”—appeared, as shown in Figure 7b. The message disappeared automatically once the electrode extension exceeded 5 mm. This procedure helps users develop the skill of maintaining the torch at an appropriate distance from the workpiece. Furthermore, when the electrode-to-workpiece distance exceeded the permissible range, the virtual weld bead displayed a characteristic crown formation, thereby enabling users and instructors to verify the accuracy of the welding operation through post-process inspection. This visual correspondence between electrode extension and bead morphology strengthens the ecological validity of the parameter feedback by mirroring real welding outcomes.

Research has shown that welding speed plays an important role in weld quality in terms of microstructure and mechanical properties. For example, a comparison of welding speeds of 8 mm/s and 11 mm/s showed that higher speeds resulted in finer microstructure and higher microhardness [48]. Welding speed is a critical parameter affecting weld geometry and quality. Optimum welding speed is essential for quality, as a higher speed leads to inadequate penetration, while a lower speed creates an undesirable, non-uniform grain structure. Therefore, the welding speed must be adjusted correctly in order to obtain a precise, strong, and homogeneous weld [49]. Furthermore, research has shown that in laser-GMAW hybrid welding of 5 mm, 10 mm, and 14 mm thick steel plates, welding speed directly affects the geometry of the weld cross section (e.g., weld width and penetration), and understanding the relationship between speed and heat transfer rate can help predict mechanical properties [50]. This work develops a system that provides real-time warnings when the welding torch speed falls below 5 mm/s or exceeds 10 mm/s during welding. This procedure enables users to improve their ability to maintain the appropriate welding speed.

The VR-based welding simulation system for GMAW is developed to support the acquisition of fundamental welding competencies by providing real-time, multimodal feedback through both visual cues and haptic responses. The platform enables progressive skill refinement by immediately detecting and correcting deviations such as excessive torch angles ($>15^\circ$), insufficient electrode protrusion (<5 mm), and travel speeds outside the optimal 5–10 mm/s range. Moreover, the system allows for post-weld examination of the virtual workpieces, as shown in Figure 8, making it possible to analyze bead geometry, weld pool morphology about travel speed, surface characteristics, and typical defect patterns (e.g., undercut and porosity). By closely replicating established GMAW quality-control practices while simultaneously offering instantaneous visual confirmation of welding technique, the simulator establishes a closed-loop training environment that enhances the efficiency and effectiveness of skill acquisition beyond conventional instructional methods. A sample video demonstrating the VR welding training process is included in the reference list and can be accessed online [51].

To examine the affective responses of the participants, confidence and anxiety were measured using a Likert scale questionnaire adapted from previously validated instruments in the research of welding and vocational training. The confidence elements were derived from established measures of welding-related self-efficacy and perceived competence employed in previous VR welding education studies [11,15]. In contrast, the anxiety elements were informed by instruments previously applied to assess performance-related stress and welding-specific anxiety in immersive training contexts [12]. The adaptation of elements from these existing, specialized tools was specifically conducted to maximize

the ecological validity and direct relevance of the scales to the welding domain. The use of these established instruments ensured the validity of the content and the conceptual alignment with recognized constructs in the field.

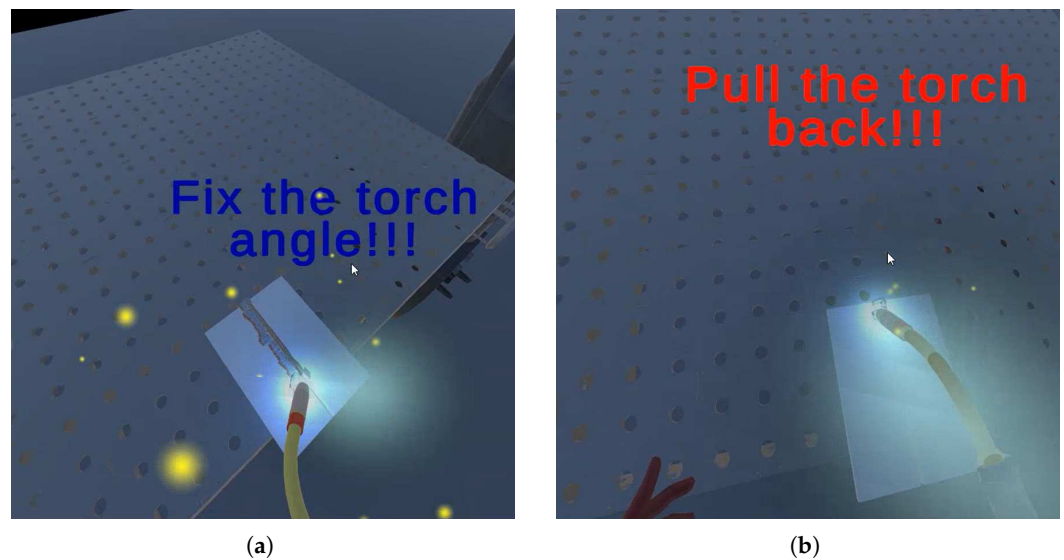


Figure 7. (a) A real-time screen capture showing a warning message displayed when the torch angle exceeds 15°. (b) A real-time screen capture showing a warning message displayed when the electrode extension distance falls below 5 mm.

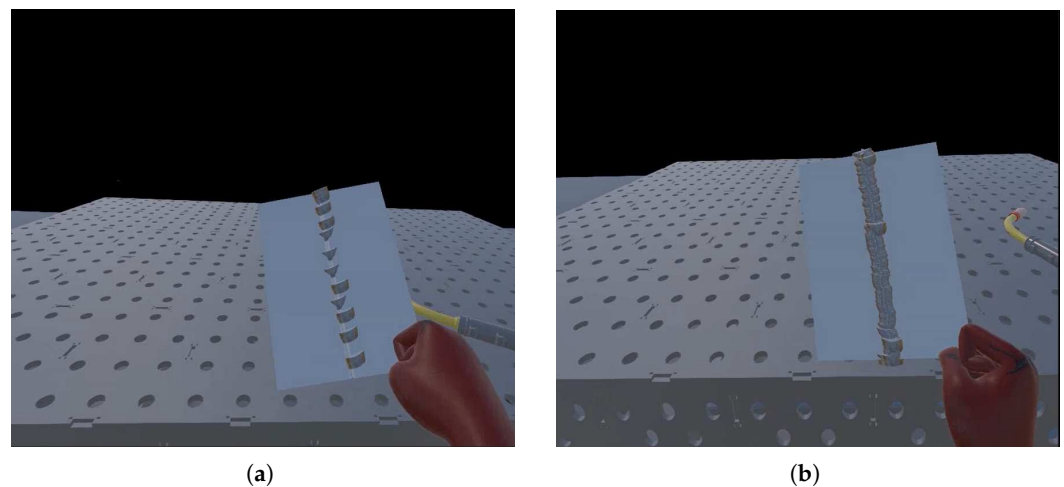


Figure 8. (a) Actual screen capture showing the resulting weld seam appearance when welding speed is high (>15 mm/s). (b) Actual screen capture showing the optimal weld seam appearance when welding speed is within the recommended range (5–10 mm/s).

4. Results

This section presents the experimental results of the VR-based welding training program. It details the demographic characteristics of the participants, quantitative data from pre- and post-training assessments, including welding knowledge, machine and gas parameter settings, safety awareness, and the impact of VR training on the participants' confidence and anxiety levels. Graphical representations further support the results to better understand the trends and significant changes observed.

4.1. Participant Demographics

A total of twenty participants with no prior welding experience were included in this study. To minimize the influence of confounding variables on learning outcomes, participants were also screened for prior welding-related skills and VR familiarity. This screening was conducted as part of the formal Informed Consent process. The Informed Consent Form included two precise screening questions to ensure participant homogeneity, requiring only binary confirmation: (1) “Do you have any prior formal or professional welding experience (e.g., in MIG/MAG, TIG, or SMAW)?” and (2) “Have you previously used any Virtual Reality (VR) headset or application?” All participants confirmed that they possessed no significant prior welding-related skills and had not previously used any VR applications. The average age of the participants was 29 years ($SD = 3.50$). The group consisted of 16 males (80%) and 4 females (20%). All participants actively participated in regular VR training sessions for two weeks, attending five sessions per week, each lasting two hours.

4.2. Assessment of Welding Knowledge

To evaluate changes in participants’ GMAW knowledge, multiple-choice tests were administered before and after the training. The test results showed that VR training had a statistically positive effect on the acquisition of theoretical welding knowledge. Before undergoing VR training, participants scored an average of 45.3 ($SD = 8.7$) on the pre-training test. After completing the VR sessions, their mean score rose to 85.1 ($SD = 6.2$), as detailed in Table 4. A paired-sample t -test confirmed that this increase was statistically significant ($t(19) = 15.2, p < 0.001$), with a large effect size (Cohen’s $d = 5.27$) and a mean difference of 39.8 points (95% CI [35.90, 43.70]). Figure 9 illustrates the average improvement in theoretical knowledge. These results indicate that the VR training substantially enhanced participants’ foundational understanding of the subject.

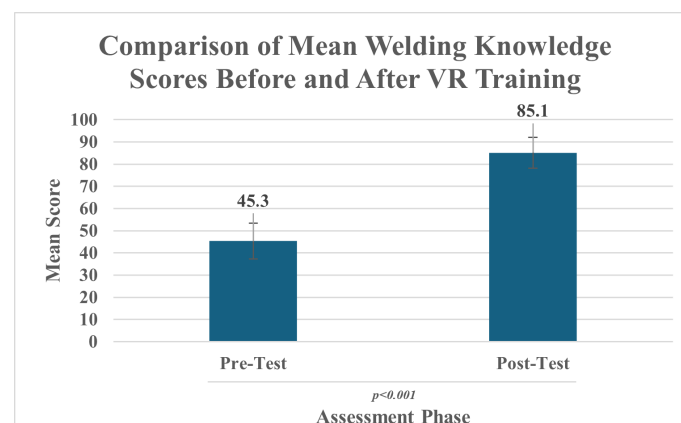


Figure 9. Comparison of mean welding knowledge scores before and after VR training.

Table 4. Comparison of pre- and post-test mean scores, standard deviations, mean differences, confidence intervals, and effect sizes for welding knowledge.

Assessment Phase	Mean Score	SD	Mean Difference (95% CI)	Cohen’s d
Pre-Test	45.3	8.7	39.8 [35.90, 43.70]	5.27
Post-Test	85.1	6.2		

4.3. Assessment of Machine and Gas Parameter Adjustment Knowledge

Analysis of the test results of the participants' knowledge and practical skills in adjusting the welding machine and gas parameters showed that the skills of the participants improved significantly after VR training. Before training, the mean score of the participants was 28.7 (SD = 5.5). In contrast, the scores after training showed a significant improvement in the mean score to 92.3 (SD = 4.8), as shown in Table 5. The paired-sample *t*-test confirmed the statistical significance of this improvement ($t(19) = 25.8, p < 0.001$), demonstrating a large effect size (Cohen's $d = 11.56$) and a mean difference of 63.6 points (95% CI [60.84, 66.36]). The significant improvement in operational control skills is visually represented in Figure 10, which illustrates the difference in mean scores before and after the intervention. The results clearly show that the VR simulation provided an effective and practical learning experience as the participants were able to effectively adjust and control key welding parameters such as the wire feed speed, voltage, current and gas flow. This dramatically improves basic familiarity with the operating controls.

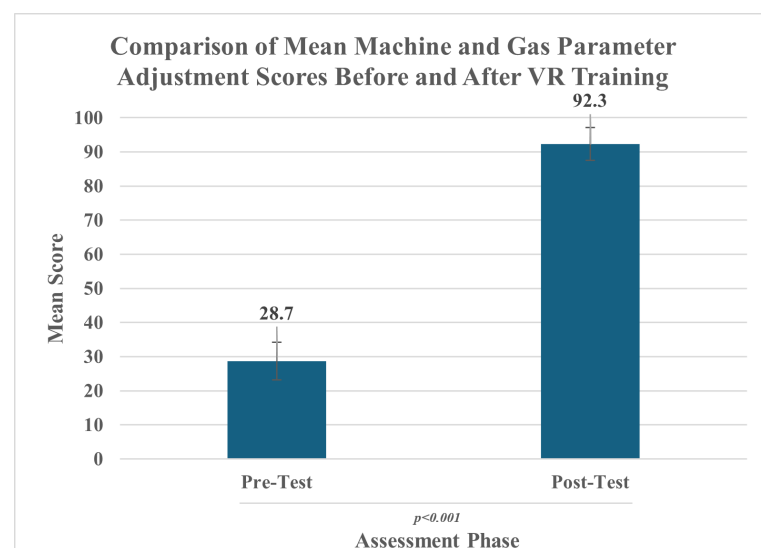


Figure 10. Comparison of machine and gas parameter adjustment scores before and after VR training.

Table 5. Comparison of pre- and post-test mean scores, standard deviations, mean differences, confidence intervals, and effect sizes for machine and gas parameter adjustment knowledge.

Assessment Phase	Mean Score	SD	Mean Difference (95% CI)	Cohen's <i>d</i>
Pre-Test	28.7	5.5	63.6 [60.84, 66.36]	11.56
Post-Test	92.3	4.8		

4.4. Findings on Confidence and Anxiety Levels

To evaluate changes in participants' confidence and anxiety levels toward welding tasks before and after the VR welding training, a Likert-scale questionnaire was administered. Analysis using paired-sample *t*-tests indicated that the program substantially enhanced participants' perceived self-efficacy while helping them manage anxiety more effectively. In this study, the adapted scales demonstrated high internal consistency, with Cronbach's alpha values of 0.89 for the confidence scale and 0.87 for the anxiety scale, confirming their reliability.

In this study, psychological readiness was conceptualized as a composite concept defined as reduced sweat anxiety and increased self-reported confidence. Assessments were conducted using an adapted Likert scale before and after VR training.

4.4.1. Changes in Confidence Levels Regarding Welding Skills

Prior to the VR training program, participants generally lacked confidence in applying basic welding techniques, operating a real welding machine, adjusting parameters such as welding torch angle, electrode extension length, and following welding procedures.

After completing the two-week VR training, the trainees' confidence in all aspects increased significantly. For "I believe I can correctly apply basic welding techniques" (item 1), the average score before the survey was 1.8 points (SD = 0.7), and it increased to 4.2 points (SD = 0.3) after the training. The confidence in operating a real welding machine also increased significantly. For "After VR training, I no longer hesitate to use a real welding machine" (item 2), the average score increased from 2.1 points (SD = 0.8) to 3.9 points (SD = 0.6).

Regarding parameter adjustment, participants indicated that their confidence in "I feel confident in adjusting parameters such as torch angle and electrode extension length when welding" (item 3) increased significantly. The mean score increased from 1.9 points (SD = 0.7) to 4.5 points (SD = 0.2). Confidence in compliance with process specifications also increased significantly. For "I feel my ability to follow welding procedures has improved after the training" (item 4), the mean score increased from 1.5 points (SD = 0.4) to 4.6 points (SD = 0.5).

The overall perception of welding self-efficacy also improved significantly. For "Overall, my confidence in my welding skills increased after VR training" (item 5), the score improved from 1.7 (SD = 0.6) before training to 4.3 (SD = 0.3) after training. The significant improvement ($p < 0.001$) for all items is shown in Figure 11, which presents the pre- and post-training scores in the form of a grouped bar chart and a line graph. Table 6 details these results by presenting the pre- and post-survey mean scores and standard deviations for each item. The results clearly show that VR-based training significantly improved the participants' confidence and perceived competence in their welding practice.

Table 6. Mean scores and standard deviations of pre- and post-survey for confidence levels regarding welding skills.

Item No.	Statement	Pre-Survey Mean (SD)	Post-Survey Mean (SD)
1	I believe I can correctly apply basic welding techniques.	1.8 (0.7)	4.2 (0.3)
2	After VR training, I no longer hesitate to use a real welding machine.	2.1 (0.8)	3.9 (0.6)
3	I feel confident in adjusting parameters such as torch angle and electrode extension length when welding.	1.9 (0.7)	4.5 (0.2)
4	I feel my ability to follow welding procedures has improved after the training.	1.5 (0.4)	4.6 (0.5)
5	Overall, my confidence in my welding skills increased after VR training.	1.7 (0.6)	4.3 (0.3)

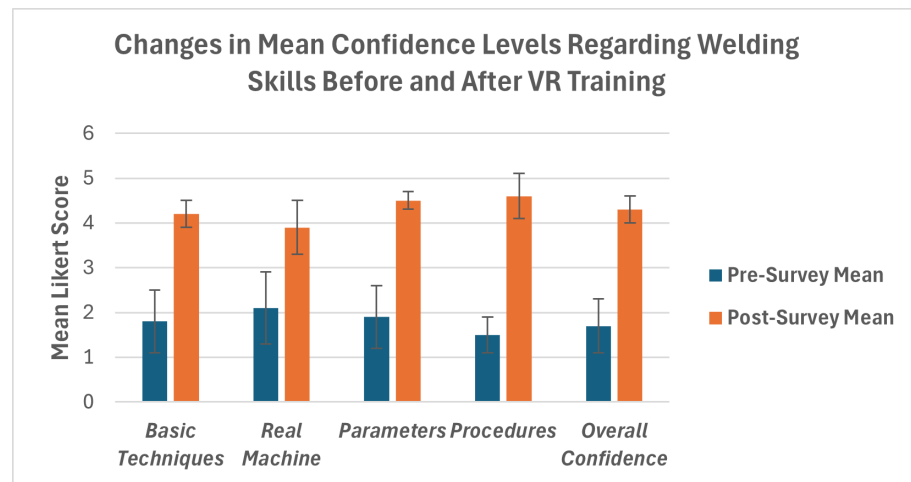


Figure 11. Changes in mean confidence levels regarding welding skills before and after VR training.

4.4.2. Changes in Anxiety Levels Regarding the Welding Environment

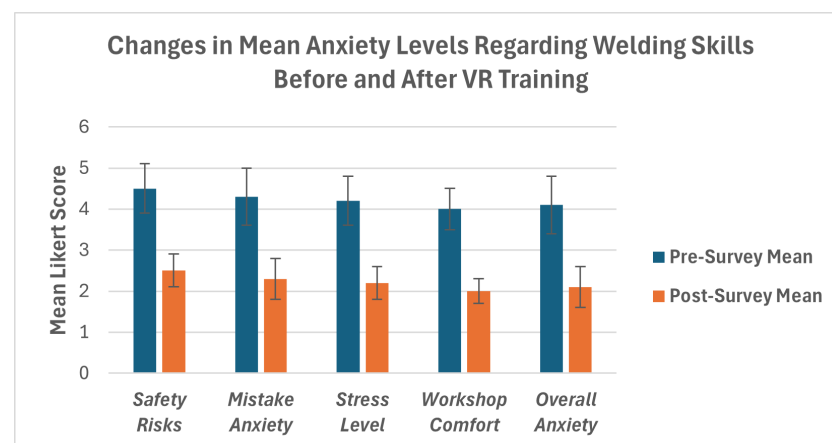
Results for anxiety levels related to the welding environment showed a significant positive impact of VR training. Prior to the training, participants reported high levels of anxiety about potential risks and discomfort in the real welding environment. For example, the pre-survey mean score for “I am concerned about the safety risks I may face in the real welding environment” (item 6) was 4.5 (SD = 0.6). Similarly, the mean score for “I feel anxious about making mistakes or harming myself while real welding” (item 7) was as high as 4.3 (SD = 0.7), and the score for “I feel stressed during the welding learning process” (item 8) was 4.2 (SD = 0.6). The discomfort that participants felt in the real welding environment was also reflected in the statement “I feel uncomfortable in a real welding workshop” (item 9), which had a mean score of 4.0 (SD = 0.5). Finally, the overall perception of welding-related anxiety, i.e., “Overall, my anxiety level regarding real welding tasks is high” (item 10), reported a mean score of 4.1 (SD = 0.7).

After completing the VR training course, all observed anxiety dimensions decreased significantly and were statistically significant. The mean score for item 6 decreased significantly to 1.5 (SD = 0.2), reflecting a significant reduction in perceived safety risk. Item 7 decreased to 1.3 (SD = 0.2), indicating a significant reduction in fear of personal error and injury. Similarly, stress associated with the welding learning process (item 8) also decreased significantly to a mean score of 1.2 (SD = 0.1). Notably, participants reported feeling more comfortable in a real-life welding environment, with a mean score of 1.1 (SD = 0.1) for item 9. In addition, the general anxiety level (item 10) also decreased significantly to 1.1 (SD = 0.1).

These findings are also shown in Table 7, where the mean scores and standard deviations for each anxiety item are presented before and after VR training. These statistically significant improvements ($p < 0.001$) are demonstrated in Figure 12, which uses a comparative visualization to present the mean scores before and after each training. The results indicate that VR-based welding training was highly effective in reducing the anxiety and discomfort of the participants and significantly improved their mental readiness for actual welding tasks.

Table 7. Mean scores and standard deviations of pre- and post-surveys for anxiety levels regarding the welding environment.

Item No.	Statement	Pre-Survey Mean (SD)	Post-Survey Mean (SD)
6	I am concerned about the safety risks I may face in the real welding environment.	4.5 (0.6)	1.5 (0.2)
7	I feel anxious about making mistakes or harming myself while real welding.	4.3 (0.7)	1.3 (0.2)
8	I feel stressed during the welding learning process.	4.2 (0.6)	1.2 (0.1)
9	I feel uncomfortable in a real welding workshop.	4.0 (0.5)	1.1 (0.1)
10	Overall, my anxiety level regarding real welding tasks is high.	4.1 (0.7)	1.1 (0.1)

**Figure 12.** Changes in mean anxiety levels regarding welding skills before and after VR training.

5. Discussion

Recent advancements in VR technologies have created significant opportunities for vocational education, particularly in disciplines where precision, safety, and cost efficiency are critical. The present study examined the effects of immersive VR-based training on the acquisition of essential welding skills, the enhancement of learners' confidence, and the reduction in performance-related anxiety.

The results demonstrated substantial improvements in both theoretical welding knowledge and practical understanding of machine operation. A paired-sample *t*-test confirmed that the increase in theoretical knowledge was statistically significant ($t(19) = 15.2$, $p < 0.001$).

The improvements observed extend beyond statistical significance, as evidenced by large effect sizes across both technical domains. The magnitude of the enhancement in theoretical knowledge acquisition (Cohen's $d = 5.27$) and technical parameter adjustment proficiency ($d = 11.56$) substantially exceeds conventional thresholds for significant effects ($d > 0.8$), as clearly demonstrated in Tables 4 and 5. The precision of these estimates is further supported by the narrow 95% confidence intervals surrounding the mean differences [39.8 points, 95% CI [35.90, 43.70] for knowledge; 63.6 points, 95% CI [60.84, 66.36] for parameter adjustment], indicating robust effect estimation and reinforcing the validity of the conclusions regarding VR-based welding training efficacy. Furthermore, due to the highly

significant p -values reported across all twelve paired-sample comparisons ($p < 0.001$ for all objective and affective measures), the findings remain statistically robust even following stringent correction for multiple comparisons (e.g., Bonferroni correction), confirming the rigor of the statistical conclusions.

These exceptionally high effect sizes substantially exceed typical meta-analytic findings reported in the broader VR training literature, where Cohen's d typically ranges between 0.6 and 0.9. This divergence can be attributed to the distinctive methodological characteristics of our training protocol. First, our participant cohort consisted exclusively of absolute novices with no prior welding experience, resulting in learning gains measured from a near-zero baseline. Second, the study implemented a systematic, two-week, repetitive training program rather than a single, short intervention. We hypothesize that the combination of true novice learners and extended, repeated practice amplified the observable improvements in technical knowledge and machine adjustment competence, thereby producing these unusually large effect sizes. Consequently, the results highlight the transformative potential of VR for fundamental skill acquisition among beginning learners.

As illustrated in Figure 9, participants' average welding knowledge score increased markedly, from 45.3 prior to training to 85.1 after training. These gains can be attributed to targeted instructional components, such as maintaining the correct torch angle—which directly affects weld pool formation and penetration depth [40]—and the precise control of travel speed, which is crucial for regulating heat input and bead geometry [42]. These findings are consistent with prior research emphasizing that VR provides an engaging and interactive learning environment in which complex technical concepts and practical skills are effectively communicated through visual, tactile, and auditory cues [6].

In addition to technical proficiency, the VR training produced noteworthy improvements in participants' psychological outcomes. As shown in Figure 11, pre-survey results indicated low self-confidence across welding tasks, with mean scores ranging from 1.5 to 2.1. Following the training, confidence levels increased significantly, reaching post-survey mean scores of 3.9 to 4.6. This improvement underscores the role of VR as a safe and repeatable practice environment that allows learners to experiment, make mistakes without material or safety consequences, and gradually build self-efficacy. These outcomes reinforce previous studies highlighting VR's potential to strengthen learner confidence in skill acquisition [6].

However, one potential limitation frequently highlighted in the literature on VR-based training is the possibility of inducing overconfidence due to the inherently risk-free nature of the virtual environment. To address this concern, the developed system integrates haptic safety feedback. Specifically, during welding practice, when the user's virtual hand meets the workpiece, the controller delivers vibration feedback that simulates potential hazards. This design choice reinforces occupational safety awareness by reminding learners of the risks associated with inappropriate hand positioning, thereby preventing unrealistic perceptions of invulnerability while still supporting confidence development.

In addition to the documented pedagogical and psychological benefits, scalability is a critical factor for the industrial applicability of VR-based training. The developed system is inherently adaptable for concurrent use, as multiple headsets can be operated simultaneously within the same training session. This allows several trainees to practice in parallel, thereby increasing throughput and reducing training time per cohort. Furthermore, the system supports instructor monitoring through cloud-based data collection, enabling trainers to remotely observe learners' performance, track progress in real time, and generate individualized feedback reports. Such scalability features enhance the feasibility of integrating VR welding simulators into industrial training programs, where efficiency, standardization, and large-scale workforce development are essential.

Equally important were the reductions observed in reported anxiety levels. Prior to the intervention, participants expressed high levels of anxiety associated with safety risks, potential mistakes, and the stress of working in a real workshop, with mean scores ranging from 4.0 to 4.5 (Figure 12). Post-training measures revealed a substantial decrease, with scores dropping to 1.1–1.5. This reduction suggests that VR simulations can mitigate performance-related stress by replicating high-risk scenarios in a controlled environment, thereby fostering familiarity and resilience. Such findings align with research demonstrating the value of VR in preparing learners to manage stress and anxiety in real-world contexts [52].

Taken together, these findings hold important implications for both vocational training and industrial practice. VR-based welding training offers a safer, more cost-effective, and scalable alternative to traditional approaches that typically involve high-cost materials and inherent safety hazards. The observed improvements in both technical competence and psychological readiness suggest that VR not only accelerates skill acquisition but also prepares learners to perform with greater confidence and reduced anxiety, thereby contributing to safer and more efficient welding applications in industry.

A preliminary cost–benefit analysis indicates that while traditional workshop-based welding training requires continuous expenditure on consumables, such as filler wire, shielding gas, electrodes, and steel workpieces, estimated at approximately \$100 per trainee for a 20-h introductory module ($\approx$ \$1000 for a cohort of 10 students), VR-based training eliminates these recurring costs. Instead, it requires a one-time investment in hardware, including a Meta Quest 2 headset and a compatible PC (total $\approx$ \$1300), plus minor maintenance and software expenses of roughly \$80–100 per cohort. Although the upfront VR cost exceeds the consumables of a single traditional course, the system quickly amortizes over repeated use: after three to five training cycles, cumulative savings on materials, space, and safety requirements outweigh the initial investment. It should be noted that the current cost analysis primarily accounts for direct equipment and consumable expenses; instructor time and facility overheads were not included, as these vary widely across institutions and training contexts. These findings align with previous reports that VR simulators provide significant long-term economic advantages by reducing material consumption and minimizing accident-related expenditures [14].

The present study introduces a VR-based training system for foundational MIG/MAG welding and evaluates its outcomes in the context of prior research on VR welding education. Unlike [15], who observed no significant performance improvements following a brief one-hour session with the VRTEX[®] 360 simulator—an outcome attributed to participants' prior experience and the lack of multimodal feedback—our study targeted twenty true novices and employed a structured two-week training program. This longer training duration, with repeated and progressively more challenging practice sessions, likely contributed to the significant performance gains observed. Furthermore, by focusing exclusively on novices, the learning effect was not confounded by existing habits or prior knowledge, making improvements more pronounced. Combined with the integration of real-time visual, auditory, and haptic feedback, these factors explain why the current study achieved stronger results than those reported in [15].

Commercial platforms such as VRTEX[®] 360 and Soldamatic[®] illustrate the diversity of VR welding systems in terms of realism and technical setup. While these solutions deliver high fidelity and advanced analytics, they depend on costly proprietary hardware and extensive calibration, which restrict scalability for smaller training institutions [53]. In contrast, the Unity–Meta Quest 2 configuration used in this study achieves similar pedagogical outcomes through a portable, wireless system that requires no external tracking devices, highlighting accessibility and practicality as its main advantages [10].

A key feature of our system is the integration of real-time visual, auditory, and haptic feedback, providing a more immersive learning environment than systems with limited sensory modalities. This design aligns with the recommendations of [14], who emphasized enhancing VR welding training fidelity through accurate movement simulation and multimodal feedback. Furthermore, the system's real-time 3D visualization and interaction processing, as highlighted by [3], are critical for effective VR-based learning.

While previous work focused on soldering applications [11], our system addresses the more complex MIG/MAG process, encompassing essential operational parameters such as torch angle, electrode extension, travel speed, gas flow, and machine settings, similar to parameter-focused VR systems [3]. Importantly, our findings on objective knowledge acquisition contrast with [16], who reported that immersive VR did not enhance immediate declarative knowledge and that paper-based methods outperformed IVR in objective post-tests for vocational education. A key reason for this discrepancy may lie in the structured and extended nature of our training protocol. Whereas [16] evaluated outcomes after a single short exposure, our program spanned two weeks with repeated practice opportunities, allowing learners to consolidate both procedural and declarative knowledge over time. Additionally, our participant pool consisted entirely of novices with no prior welding experience, which reduced ceiling effects and amplified observable learning gains. The integration of multimodal feedback (visual, auditory, and haptic) also provided a richer learning environment compared to the IVR systems in [16]. These methodological differences likely explain why the present study yielded stronger improvements in both objective knowledge and affective outcomes.

These psychological benefits are further supported by [13], who reported that VR positively influences cognitive, behavioral, and affective engagement, including motivation and learning efficacy, while also aiding in emotion regulation. In contrast to [12], who found persistent anxiety despite VR exposure, our findings indicate that VR simulations can effectively mitigate performance-related stress by replicating high-risk scenarios in a controlled environment. Collectively, these results underscore the pedagogical novelty of our system, which combines comprehensive multimodal feedback with cost-effective and accessible hardware—a factor highlighted by [10] as critical for the broader implementation of VR welding simulators, particularly for the initial training of novice welders, allowing repeated practice in safe conditions.

Despite these promising findings, the study has several notable limitations that restrict the scope of generalization. First, the relatively small sample size ($n = 20$) reduces statistical power and limits the representativeness of the results. Future studies should recruit larger and more heterogeneous samples, including participants with varying levels of welding experience and different demographic characteristics, such as educational background and technical aptitude, to strengthen external validity. Second, the two-week training period, although sufficient for capturing short-term effects, is insufficient to assess the durability and decay of learned skills, skill transfer to real-world welding tasks, and the sustainability of psychological benefits, such as reduced anxiety. To strengthen the pedagogical implications regarding skill mastery, future research must explicitly incorporate longitudinal follow-up measurements (e.g., three to six months) to track the persistence, retention, and transferability of acquired skills to real welding environments, thereby evaluating how VR training translates into enduring professional competence. Third, the study did not evaluate how effectively VR-acquired skills translate into actual workshop performance over time, which remains a crucial step toward validating the ecological validity of VR-based training. Future investigations should therefore include longitudinal and transfer-of-training analyses. The system's modular design, leveraging the portable, wireless Meta Quest 2 platform and replicating the authentic control interface of the Magmaweld RS300 MK machine, estab-

lishes a robust architectural foundation for sensor-based integration with external physical welding equipment required for future Mixed Reality (MR) transfer validation. Additionally, although large effect sizes were observed, they should be interpreted cautiously, as they may reflect short-term performance gains rather than enduring skill mastery.

Extended training durations and longitudinal follow-up measurements would provide deeper insights into the durability of learning outcomes. Third, the exclusive reliance on self-reported survey data for confidence and anxiety introduces the risk of subjective bias. Incorporating objective performance-based measures obtained from real welding tasks could improve the robustness of the conclusions. Finally, the VR environment focused on fundamental MIG/MAG welding tasks only; therefore, its applicability to complex, industrial-level welding scenarios and different welding processes (e.g., TIG or SMAW) remains to be validated in future research. Further refinement of the system should also consider incorporating more realistic thermal effects, variable material types, and multi-pass welding processes to increase fidelity and industrial relevance.

Another limitation of this study is the limited sample size ($n = 20$) and the gender imbalance among participants, with 80% male and only 20% female trainees. Such a small and demographically uneven sample constrains the statistical power of the analyses and limits the extent to which the findings can be generalized to broader populations. Previous research suggests that gender-related differences may influence factors such as self-efficacy, perceived competence, and anxiety responses in technical learning contexts. Therefore, while the results of this study indicate strong learning gains and significant reductions in anxiety, they should be interpreted with caution due to these demographic limitations. Future research should recruit a larger and more gender-balanced cohort to verify the reproducibility of the findings and to explore whether VR-based welding training can help mitigate gender disparities in technical education outcomes.

Future research should incorporate objective, performance-based evaluations derived from real welding tasks and apply longitudinal designs to assess the durability of acquired skills and mitigate the threat of skill decay.

In this study, welding performance was assessed within the VR environment through bead geometry and surface characteristics, reflecting learners' control of torch angle, travel speed, and electrode-to-workpiece distance. While such measures indicate procedural accuracy, they cannot substitute for destructive or mechanical testing of physical welds. Accordingly, forthcoming studies should validate weld quality in real workshop conditions and extend simulations to cover critical real-world challenges such as joint preparation, material thickness variations, and thermal effects (e.g., residual stress and material warping). To enhance ecological validity, future systems should integrate these modules and correlate outcomes with standardized destructive and non-destructive tests. Moreover, future research should establish appropriate control groups—such as participants receiving conventional, instructor-led welding training and those without intervention—to enable direct comparison with the VR-trained cohort. Such comparative designs will make it possible to determine whether the observed performance and psychological improvements truly result from VR-based training, thereby strengthening causal inferences and internal validity. Recording and visualizing individual learning curves across sessions will further capture progression patterns and variability. In addition, longitudinal follow-up studies should be conducted to track learners over extended periods (e.g., three to six months) after VR training to determine the persistence, retention, and transferability of acquired skills to real welding environments. Evaluating the long-term effects of VR-based instruction—such as sustained hand–eye coordination, procedural memory, and accuracy under real workshop conditions—will provide a more comprehensive understanding of how VR training translates into enduring professional competence. Finally, controlled studies

should directly examine whether competencies developed in VR translate into workshop performance, using standardized metrics such as bead geometry, penetration depth, defect rates, and mechanical strength of welded joints.

6. Conclusions

The findings of this study demonstrate that immersive VR-based welding training constitutes a practical and innovative approach to vocational education. By providing a safe, repeatable, and psychologically supportive environment, VR not only enhances technical proficiency but also strengthens learner confidence while mitigating training-related anxiety. These results highlight the potential of VR to overcome the fundamental constraints of traditional workshop-based instruction and to facilitate a more efficient transfer of theoretical knowledge to practical competence.

From a pedagogical standpoint, VR fosters active, experiential learning, thereby aligning with contemporary principles of motivation, self-efficacy, and learner-centered instruction. From an industrial perspective, it offers a scalable and cost-effective training solution that reduces material consumption, minimizes safety risks, and accelerates the development of critical skills. Consequently, VR-based systems hold considerable promise for both modernizing vocational curricula and addressing skilled labor shortages in sectors such as manufacturing and construction.

Notwithstanding these promising results, the study is limited by its relatively modest sample size and short-term focus. Future research should employ longitudinal designs to examine skill retention and potential skill decay over extended periods of time, involve more diverse participant groups to enhance generalizability, systematically collect detailed demographic data (e.g., educational background and technical aptitude), and develop advanced training modules that address complex welding processes (beyond MIG/MAG, such as TIG or SMAW) and meet industry-specific requirements. Such investigations will be essential to validating the sustainability of the observed benefits and ensuring the broader applicability of VR-based training in high-risk, skill-intensive domains.

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Abbreviations

The following abbreviations are used in this manuscript:

VR	Virtual Reality
GMAW	Gas Metal Arc Welding
MIG	Metal Inert Gas
MAG	Metal Active Gas
HMD	Head-Mounted Display
L/min	Liters per Minute
SD	Standard Deviation

References

1. Sacks, R.; Perlman, A.; Barak, R. Construction Safety Training Using Immersive Virtual Reality. *Constr. Manag. Econ.* **2013**, *31*, 1005–1017. [\[CrossRef\]](#)
2. Jensen, L.; Konradsen, F. A Review of The Use of Virtual Reality Head-Mounted Displays in Education and Training. *Educ. Inf. Technol.* **2018**, *23*, 1515–1529. [\[CrossRef\]](#)
3. Tran, N.H.; Nguyen, V.N.; Bui, V.T. Development of A Virtual Reality-Based System for Simulating Welding Processes. *Appl. Sci.* **2023**, *13*, 6082. [\[CrossRef\]](#)
4. Chan, V.S.; Haron, H.N.H.; Isham, M.I.B.M.; Mohamed, F.B. VR and AR virtual welding for psychomotor skills: A systematic review. *Multimed. Tools Appl.* **2022**, *81*, 12459–12493. [\[CrossRef\]](#)
5. Bader, S.; Abotaleb, I.; Hosny, O. Utilization of Adult I-Learning Theories for Effective Virtual Reality Safety Training in Construction. *J. Civ. Eng. Educ.* **2025**, *151*, 04025002. [\[CrossRef\]](#)
6. Sung, H.; Kim, M.; Park, J.; Shin, N.; Han, Y. Effectiveness of Virtual Reality in Healthcare Education: Systematic Review and Meta-Analysis. *Sustainability* **2024**, *16*, 8520. [\[CrossRef\]](#)
7. Yang, F.; Zhang, J. Virtual Construction Safety Training System: How Does it Relate to and Affect Users' Emotions. In Proceedings of the 41st International Symposium on Automation and Robotics in Construction (ISARC 2024), Lille, France, 3–5 June 2024; The International Association for Automation and Robotics in Construction: Lille, France, 2024; pp. 599–606. [\[CrossRef\]](#)
8. Marron, T.; Dungan, N.; Namee, B.; Hagan, A. Virtual Reality Pilot Training: Existing Technologies, Challenges Opportunities. *J. Aviat. Educ. Res.* **2024**, *33*, 1980.
9. Chen, J.; Dai, J.; Zhu, K.; Xu, L. Effects of Extended Reality on Language Learning: A Meta-Analysis. *Front. Psychol.* **2022**, *13*, 1016519. [\[CrossRef\]](#)
10. Michalak, D.; Rozmus, M.; Tokarczyk, J.; Szeferda, K. Portable VR Welding Simulator. *Appl. Sci.* **2024**, *14*, 7687. [\[CrossRef\]](#)
11. Alfaro-Viquez, D.; Zamora-Hernández, M.; Fernández-Vega, M.; García-Rodríguez, J.; Azorín-López, J. Integrating Virtual Reality Into Welding Training: An Industry 5.0 Approach. *Electronics* **2025**, *14*, 1964. [\[CrossRef\]](#)
12. Preston, B.; Stone Richard, T.; Ryan, A. Reducing Beginning Welders' Anxiety by Integrating Virtual Reality Simulations. *Int. J. Agric. Technol.* **2025**, *5*, 1–8. [\[CrossRef\]](#)
13. Lin, X.P.; Li, B.B.; Yao, Z.N.; Yang, Z.; Zhang, M. The Impact of Virtual Reality on Student Engagement in the Classroom-A Critical Review of the Literature. *Front. Psychol.* **2024**, *15*, 1360574. [\[CrossRef\]](#)
14. Heibel, B.; Anderson, R.; Drewery, M. Virtual Reality in Welding Training and Education: A Literature Review. *J. Agric. Educ.* **2023**, *64*. [\[CrossRef\]](#)
15. Wells, T.; Miller, G. The Effect of Virtual Reality Technology on Welding Skill Performance. *J. Agric. Educ.* **2020**, *61*, 152–171. [\[CrossRef\]](#)
16. Thomann, H.; Zimmermann, J.; Deutscher, V. How Effective is Immersive VR For Vocational Education Analyzing Knowledge Gains and Motivational Effects. *Comput. Educ.* **2024**, *220*, 105127. [\[CrossRef\]](#)
17. Yan, C.; Mohamed, H.B. The Role of Virtual Reality in Education: Impact on Self-Efficacy, Cost, Cross-Cultural Learning, and Interaction. *Int. J. Acad. Res. Progress. Educ. Dev.* **2025**, *14*, 86–112. [\[CrossRef\]](#)
18. Dinçer, S.G.; Dilek, H.Y. 3D Printing and Virtual Reality in the Study of Muqarnas: A Comparative Approach. *Ain Shams Eng. J.* **2025**, *16*, 103742. [\[CrossRef\]](#)
19. Balz, A.; Forjan, M. Technology Enhanced Training in Medical Multi-User Scenarios. In Proceedings of the European Conference on Technology Enhanced Learning, Aveiro, Portugal, 4–8 September 2023; pp. 680–685. [\[CrossRef\]](#)
20. Afolabi, A.; Ige, A.; Akinade, A.; Adepoju, P. Virtual Reality and Augmented Reality: A Comprehensive Review of Transformative Potential in Various Sectors. *Magna Scientia Adv. Res. Rev.* **2023**, *7*, 107–122. [\[CrossRef\]](#)
21. Kang, X.; Zhang, Y.; Sun, C.; Zhang, J.; Che, Z.; Zang, J.; Zhang, R. Effectiveness of Virtual Reality Training in Improving Outcomes for Dialysis Patients: Systematic Review and Meta-Analysis. *J. Med. Internet Res.* **2025**, *27*, e58384. [\[CrossRef\]](#) [\[PubMed\]](#)

22. Kafes, M.; Ileri, Y.Y. Current Status of Virtual Reality Researches at Healthcare: Thematic and Bibliometric Analysis. *Front. Virtual Real.* **2025**, *6*, 1411075. [\[CrossRef\]](#)
23. Checa, D.; Saucedo-Dorantes, J.J.; Osornio-Rios, R.A.; Antonino-Daviu, J.A.; Bustillo, A. Virtual Reality Training Application for the Condition-Based Maintenance of Induction Motors. *Appl. Sci.* **2022**, *12*, 414. [\[CrossRef\]](#)
24. Moser, T.; Schlager, A. Training and Assistance in Industrial Environments Using Extended Reality. In Proceedings of the 2024 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW), Orlando, FL, USA, 16–21 March 2024; pp. 97–103. [\[CrossRef\]](#)
25. Lan, G.; Lai, Q.; Bai, B.; Zhao, Z.; Hao, Q. A Virtual Reality Training System for Automotive Engines Assembly and Disassembly. *IEEE Trans. Learn. Technol.* **2023**, *17*, 754–764. [\[CrossRef\]](#)
26. Hirt, C.; Spahni, M.; Kompis, Y.; Jetter, D.; Kunz, A. Virtual Reality Training Platform for A Computer Numerically Controlled Grinding Machine Tool. *Int. J. Mechatron. Manuf. Syst.* **2021**, *14*, 1–17. [\[CrossRef\]](#)
27. Lu, Q.; Shen, X.; Zhou, J.; Li, M. MBD-Enhanced Asset Administration Shell for Generic Production Line Design. *IEEE Trans. Syst. Man, Cybern. Syst.* **2024**, *54*, 5593–5605. [\[CrossRef\]](#)
28. Abotaleb, I.; Hosny, O.; Nassar, K.; Bader, S.; Elrifaa, M.; Ibrahim, S.; El Hakim, Y.; Sherif, M. An Interactive Virtual Reality Model for Enhancing Safety Training in Construction Education. *Comput. Appl. Eng. Educ.* **2023**, *31*, 324–345. [\[CrossRef\]](#)
29. van Weelden, E.; Alimardani, M.; Wiltshire, T.J.; Louwerse, M.M. Advancing the Adoption of Virtual Reality and Neurotechnology to Improve Flight Training. In Proceedings of the 2021 IEEE 2nd International Conference on Human-Machine Systems (ICHMS), Magdeburg, Germany, 8–10 September 2021; pp. 1–4. [\[CrossRef\]](#)
30. Paszkiewicz, A.; Salach, M.; Wydrzyński, D.; Woźniak, J.; Budzik, G.; Bolanowski, M.; Ganzha, M.; Paprzycki, M.; Cierpicki, N. Use of Virtual Reality to Facilitate Engineer Training in the Aerospace Industry. *Mach. Graph. Vis.* **2023**, *32*, 19–44. [\[CrossRef\]](#)
31. Jo, J.W.; Kim, Y.; Jung, S.M.; Kim, J.M. Progress in 3D Display Technologies for Immersive Visual Experiences. *IEEE Open J. Immersive Disp.* **2024**, *1*, 155–164.
32. Özer, Ş. Sanal Gerçeklik Teknolojilerinde Dokunsal Geri Bildirim: Eğitim Amaçlı Kullanımı Üzerine Yazın İncelemesi [Haptic Feedback in Virtual Reality Technologies: A Literature Review on Educational Use]. *J. Econ. Political Sci.* **2023**, *3*, 147–156.
33. Bailenson, J. *Experience on Demand: What Virtual Reality Is, How It Works, and What It Can Do*; W.W. Norton & Company: New York, NY, USA, 2018.
34. Angra, S.; Jangra, S.; Gulzar, Y.; Sharma, B.; Singh, G.; Onn, C.W. Twenty-Two Years of Advancements in Augmented and Virtual Reality: A Bibliometric and Systematic Review. *Front. Comput. Sci.* **2025**, *7*, 1470038. [\[CrossRef\]](#)
35. Haas, J.K. A History of the Unity Game Engine. Master's Thesis, Worcester Polytechnic Institute, Worcester, MA, USA, 2014.
36. Warburton, M.; Mon-Williams, M.; Mushtaq, F.; Morehead, J.R. Measuring Motion-to-Photon Latency for Sensorimotor Experiments With Virtual Reality systems. *Behav. Res. Methods* **2023**, *55*, 3658–3678. [\[CrossRef\]](#)
37. Abdulkarim, D.; Di Luca, M.; Aves, P.; Maaroufi, M.; Yeo, S.H.; Miall, R.C.; Holland, P.; Galea, J.M. A Methodological Framework to Assess the Accuracy of Virtual Reality Hand-Tracking Systems: A Case Study with The Meta Quest 2. *Behav. Res. Methods* **2024**, *56*, 1052–1063. [\[CrossRef\]](#)
38. Kou, S. *Welding Metallurgy*; Wiley-Interscience: New York, NY, USA, 1987. [\[CrossRef\]](#)
39. Weman, K. *Welding Processes Handbook*; Elsevier Science: Amsterdam, The Netherlands, 2011. [\[CrossRef\]](#)
40. Jeffus, L.F.; Johnson, H.V.; Lesnewich, A. *Welding: Principles and Applications*, 6th ed.; Delmar Cengage Learning: Clifton Park, NY, USA, 2008.
41. Magmaweld. User Manual: UM RSMK200/400, 2023. Available online: https://www.magmaweld.com/Content/UserFiles/OerlikonKutuphanesi/UM_RSMK200_400_022022_012023_002_156.pdf (accessed on 25 October 2025).
42. Easterling, K. *Introduction to the Physical Metallurgy of Welding*, 2nd ed.; Elsevier: Amsterdam, The Netherlands, 2013.
43. Yao, P.; Tang, H.; Zhou, K.; Lin, H.; Xu, Z.; Du, X. Influence of Inclination of Welding Torch on Weld Bead During Pulsed-GMAW Process. *Materials* **2020**, *13*, 2652. [\[CrossRef\]](#) [\[PubMed\]](#)
44. Lee, H.; Ji, C.; Yu, J. Effects of Welding Current and Torch Position Parameters on Bead Geometry in Cold Metal Transfer Welding. *J. Mech. Sci. Technol.* **2018**, *32*, 4335–4343. [\[CrossRef\]](#)
45. American Welding Society (AWS). *Structural Welding Code-Steel*; Mar Lin Publishing: Miami, FL, USA, 1978.
46. Shah, A.; Aliyev, R.; Zeidler, H.; Krinke, S. A Review of the Recent Developments and Challenges in Wire Arc Additive Manufacturing (WAAM) Process. *J. Manuf. Mater. Process.* **2023**, *7*, 97. [\[CrossRef\]](#)
47. e Silva, R.H.G.; dos Santos Paes, L.E.; Barbosa, R.C.; Sartori, F.; Schwedersky, M.B. Assessing the Effects of Solid Wire Electrode Extension (Stick Out) Increase in MIG/MAG Welding. *J. Braz. Soc. Mech. Sci. Eng.* **2018**, *40*, 31. [\[CrossRef\]](#)
48. Xiao, N.; Kong, H.; Sun, Q.; Ma, N. Study of Process, Microstructure, and Properties of Double-Wire Narrow-Gap Gas Metal Arc Welding Low-Alloy Steel. *Materials* **2024**, *17*, 6183. [\[CrossRef\]](#)
49. Baghel, P.K. Effect of SMAW Process Parameters on Similar and Dissimilar Metal Welds: An Overview. *Heliyon* **2022**, *8*, e12161. [\[CrossRef\]](#)

50. Naikun, W.; Jin, S.; Rundang, Y.; Juntong, X.; Sheng, G.; Xiaomeng, L.; Aimin, X.; Huijun, P.; Shuai, Y.; Chun, Y.; et al. Prediction of Cross-Sectional Shape, Microstructure and Mechanical Properties of Full Penetration Laser-GMAW Welded Butt Joints. In Proceedings of the International Conference on Robotic Welding, Intelligence and Automation, Shanghai/Lanzhou, China, 16–18 December 2022; pp. 23–41. [\[CrossRef\]](#)
51. Koçak, N.F.; Saygın, A.; Türk, F. Sample VR Welding Training Video. 2025. Available online: <https://www.youtube.com/watch?v=B8bXD8RyPo8> (accessed on 25 October 2025).
52. Botella, C.; García-Palacios, A.; Villa, H.; Baños, R.; Quero, S.; Alcañiz, M.; Riva, G. Virtual Reality Exposure in the Treatment of Panic Disorder and Agoraphobia: A Controlled Study. *Clin. Psychol. Psychother. Int. J. Theory Pract.* **2007**, *14*, 164–175. [\[CrossRef\]](#)
53. Ipsita, A.; Erickson, L.; Dong, Y.; Huang, J.; Bushinski, A.K.; Saradhi, S.; Villanueva, A.M.; Peppler, K.A.; Redick, T.S.; Ramani, K. Towards Modeling of Virtual Reality Welding Simulators to Promote Accessible and Scalable Training. In Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems, New Orleans, LA, USA, 29 April–5 May 2022; pp. 1–21. [\[CrossRef\]](#)

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