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COMPARATIVE EFFECTIVENESS OF VIRTUAL REALITY VS. AUGMENTED REALITY IN WELDING OPERATOR TRAINING

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Purpose: This study investigates the comparative effectiveness of Virtual Reality (VR) and Augmented Reality (AR) technologies in welding operator training, with a focus on perceived realism and potential for skill transfer. Given the high-risk nature of welding, the research explores safer and more efficient alternatives to traditional hands-on instruction.
Design/methodology/approach: A total of 40 certified welders with at least five years of experience participated in a controlled comparison of VR and AR training systems at a laboratory in the Walbrzych Special Economic Zone in Poland. Both systems were enhanced with standardized instructions based on the Training Within Industry (TWI) Job Instruction method. After practicing the same welding task in both environments, participants rated the realism of each experience using a 5-point Likert scale. A paired sample t-test was used to assess statistical significance.
Findings: The results show that AR training was perceived as significantly more realistic than VR, with average ratings of 4.13 and 2.55 respectively. Participants highlighted the physical interaction with real tools and objects in AR as a major factor contributing to this realism. VR, while immersive and safe, lacked haptic feedback and physical context, which reduced its perceived authenticity. The findings support the use of AR for enhancing skill transfer and suggest a blended training model using both technologies.
Research limitations/implications: This study focuses on subjective assessments of realism without measuring actual skill improvement post-training. Future research should incorporate objective performance evaluations and explore long-term learning outcomes.
Practical implications: The study provides evidence for training designers and manufacturers on how to integrate AR and VR in welding instruction. AR shows promise for improving trainee readiness and reducing material costs, while VR remains valuable for safe repetition of basic techniques.
Originality/value: The article offers a novel comparison of VR and AR in the context of welding, based on evaluations from experienced welders rather than novices. It also integrates the TWI Job Instruction method into both training environments, providing a standardized instructional foundation for fair comparison and improved consistency.
Keywords: Welding training; Virtual Reality; Augmented Reality; Safety; Training Within Industry (TWI); Job Instruction; Skill transfer; Industrial training.
Category of the paper: Research paper.

Introduction

Welding is a fundamental industrial process used to join metal components in sectors ranging from construction and manufacturing to shipbuilding and automotive production (Kumar, Dharanipriya, 2014). It involves fusing materials by applying intense heat and sometimes pressure, often creating an electrical arc that can reach temperatures over 5000°C. The very nature of welding makes it one of the most dangerous technical occupations. Operators are routinely exposed to multiple hazards (Mozzoni et al., 2020; Pirvu et al., 2024): extreme heat and bright ultraviolet light from the welding arc, electrical currents, hazardous fumes and gases. Common injuries among welders include skin burns, eye injuries (corneal flash burns, cataracts), hearing loss, metal fume fever, and acute pneumonia (Bayram et al., 2016; Mozzoni et al., 2020; Ahn et al., 2023).

Given these risks, ensuring welders are thoroughly trained in safe practices is paramount. Traditional welding instruction often involves hands-on practice with real equipment, which itself carries intrinsic dangers and significant costs (Carter et al., 2006; Christian et al., 2009). Novice welders learning on actual workpieces risk injuring themselves or others and can damage expensive materials or tools due to mistakes. Conventional training also incurs high material consumption (metal coupons, electrodes, gas) and requires experienced instructors to physically supervise each trainee (Pribadi et al., 2024). Technology-enhanced training has emerged to fill this need. In particular, Virtual Reality (VR) and Augmented Reality (AR) systems allow trainees to practice welding in simulated environments that eliminate physical danger while providing realistic feedback (Pribadi et al., 2024; Alfaro-Viquez et al., 2025). VR immerses the user completely in a computer-generated world. AR overlays digital simulations onto the user's view of the real world, permitting training with real tools and objects enhanced by virtual guidance or feedback.

This article compares VR and AR training systems deployed at an Educational Laboratory in the Walbrzych Special Economic Zone, focusing on their effectiveness in mirroring real welding conditions and improving operator readiness. We hypothesize that AR, which allows interaction with physical tools and the real environment, will provide a stronger sense of realism and skill fidelity than VR.

Literature Review

VR-based training can significantly reduce workplace accidents by allowing workers to experience and learn from simulated hazards in a safe setting (Mozzoni et al., 2020). In construction safety studies, trainees who practiced in immersive VR environments demonstrated better hazard recognition and safety compliance compared to those with traditional training (Sacks et al., 2013; Stefan et al., 2023). VR also enables unlimited repetition of scenarios, crucial for mastering high-risk skills like welding (Alfaro-Viquez et al., 2025). However, research suggests that the effectiveness of VR/AR training depends on how closely the simulation matches real tasks. Realism and skill transfer are key: the closer the training experience is to actual welding, the more likely skills will transfer to real operations (Pribadi et al., 2024; Alfaro-Viquez et al., 2025). A systematic review of 136 studies concluded that VR is broadly effective for safety and technical skills training, especially when evaluations show improved learning and user engagement (Stefan et al., 2023; Chan et al., 2022). AR supports situated learning and may outperform VR when physical manipulation is essential. It has been shown to produce equal or better student outcomes than traditional training while significantly lowering material use (Michalak et al., 2024). In ergonomic and procedural tasks, AR results in higher task accuracy and shorter learning times than VR (Ai et al., 2024; Liu et al., 2022). Users often report that AR feels more like "the real thing" because they can manipulate tangible items, unlike VR which lacks physical cues (Pribadi et al., 2024).

An important but often overlooked factor in simulation-based training is the consistency and structure of the instructional content. The Training Within Industry (TWI) Job Instruction method has been recognized for its ability to standardize and improve workplace training (Dinero, 2005). TWI emphasizes breaking down a task into clearly defined steps, key points, and underlying reasons, ensuring trainees receive uniform and high-quality instruction (Misiurek, 2016; Misiurek, Misiurek, 2017). Studies show that applying TWI improves employee competence and reduces training variability, which is particularly relevant in high-risk contexts like welding (Wrona, Graupp, 2006). Despite its proven effectiveness, the integration of TWI into VR/AR training programs remains underexplored, presenting an opportunity to enhance the structure and efficacy of immersive training solutions.

Methods

1. Participants

We invited 40 certified welders participated in the study. All held welding certifications (at least European or AWS Certified Welder status) and had a minimum of 5 years of field experience. This experienced group was selected to ensure informed assessments of training realism.

2. Equipment and Procedure

Each participant trained on both VR and AR systems by completing a standard bead-on-plate welding task in each modality. The sessions took place in a controlled lab setting. VR immerses the trainee in a fully synthetic environment, blocking out the physical world entirely. In our laboratory's VR welding simulator, the user wears a head-mounted display that presents a 3D virtual workshop containing welding equipment and workpieces (Figure 1). The trainee also uses input devices – in this case, a realistic mock welding torch and a sensor-tracked glove or controller – to interact with the virtual environment. As the user "welds" in VR, the system simulates the visual and auditory feedback of welding: one sees a virtual arc, melting weld pool, and sparks, and hears the crackle of the weld. The VR simulator can also provide guidance and performance feedback, for example by overlaying indicators for proper torch angle or travel speed during the simulation.

Figure 1. VR welding simulator in Walbrzych Special Economic Zone.
Source: Authors' own creation.

A major benefit of VR is safety – trainees can make mistakes (like improper angle or contact) with no risk of injury or damage (Alfaro-Viquez et al., 2025). VR also allows exercises that would be difficult or costly in reality, such as repeatedly welding the same joint type under identical conditions to practice consistency (Wells, Miller, 2020). Studies have shown that VR training can improve learners' focus and reduce distractions since the immersive experience captures their full attention (Pribadi et al., 2024; Stefan et al., 2023). On the downside, current VR technology has limitations in realism. Trainees do not feel the true weight of welding apparatus or the heat of the arc. The absence of physical forces and haptic cues can make some actions (like gauging proper electrode distance or applying correct force) less intuitive.

Furthermore, some users experience simulator sickness (motion dizziness or discomfort) in VR, especially during longer sessions (Pribadi et al., 2024). Despite these drawbacks, VR's ability to simulate hazardous scenarios without real danger makes it a powerful training tool (Mozzoni et al., 2020).

AR offers a different approach – instead of replacing reality, it augments the real-world environment with virtual elements (Pribadi et al., 2024). In our AR training system, the trainee wears a see-through AR welding helmet that overlays digital information onto their view of an actual welding station (Figure 2). The trainee holds a real or replica welding torch, and there is typically a physical workpiece (or coupon) in front of them.

Figure 2. AR welding simulator in Walbrzych Special Economic Zone.

Source: Authors' own creation.

When the trainee strikes an arc or makes a weld bead in AR, there is no real electric arc; instead, the system superimposes a virtual arc and weld onto the physical workpiece as seen through the AR display. Essentially, the user sees the real nozzle of their torch and the real metal piece, with computer-generated graphics adding the molten weld puddle, sparks, smoke, and other visual cues in correct position. In our lab's AR setup, for example, trainees practiced bead-on-plate welding on a metal coupon while the AR helmet projected a realistic molten weld pool and feedback indicators onto that coupon. The key advantage of AR is the blend of physical and virtual: because the trainee holds a real torch and works with real objects (albeit unpowered), the kinaesthetic and ergonomic aspects of welding are preserved. The weight of the torch, the need to brace oneself against a workbench, and the spatial orientation to a real workpiece all mirror actual welding conditions. This physical fidelity can enhance the sense of realism – indeed, users often report that AR feels more like "the real thing" because they can directly see and manipulate tangible items rather than only virtual representations (Alfaro-Viquez et al., 2025; Pribadi et al., 2024).

Despite these challenges, AR's ability to allow hands-on practice with real equipment under guided virtual visualization makes it extremely promising for welding education (Michalak et al., 2024). For instance, an augmented reality welding simulator was shown to produce equal or better student outcomes than traditional training, while significantly lowering material use.

VR and AR differ fundamentally in the level of immersion and the role of physical context (Pribadi et al., 2024). VR offers total immersion – useful for training scenarios like out-of-position welds or dangerous situations (e.g. welding at heights or in confined spaces) that can be simulated virtually without risk. It also allows trainees to practice endlessly without consuming real consumables, thus is cost-effective for repetitive skill drills (Pribadi et al., 2024). AR, on the other hand, provides situated learning – the trainee practices in a setting closer to the actual work environment, which can improve their muscle memory and spatial awareness for real welding tasks. Our VR simulator in Poland was often used to teach novices basic techniques (arc striking, steady travel, proper angle) in a straightforward scenario, leveraging VR's interactive guidance. The AR system was then used to bridge the gap to live welding by having trainees perform those techniques on real hardware with augmented feedback. Notably, Ai et al. (2024) found in a controlled experiment that while both VR and AR enhanced training outcomes, VR users experienced more simulator sickness, and AR users reported greater comfort with the tasks. This suggests AR might be preferable for longer practice sessions where sustaining user comfort is important. Another study observed that AR training produced higher task accuracy and shorter learning times than a comparable VR training for certain procedural tasks (Alfaro-Viquez et al., 2025).

These findings reflect our own anecdotal experience with the welding trainees: those using the AR system tended to comment on how "real" it felt to hold the actual welding torch and see it in their hands, whereas those using VR appreciated the fully immersive experience but noted it was "like a video game" and lacked the physical cues of welding.

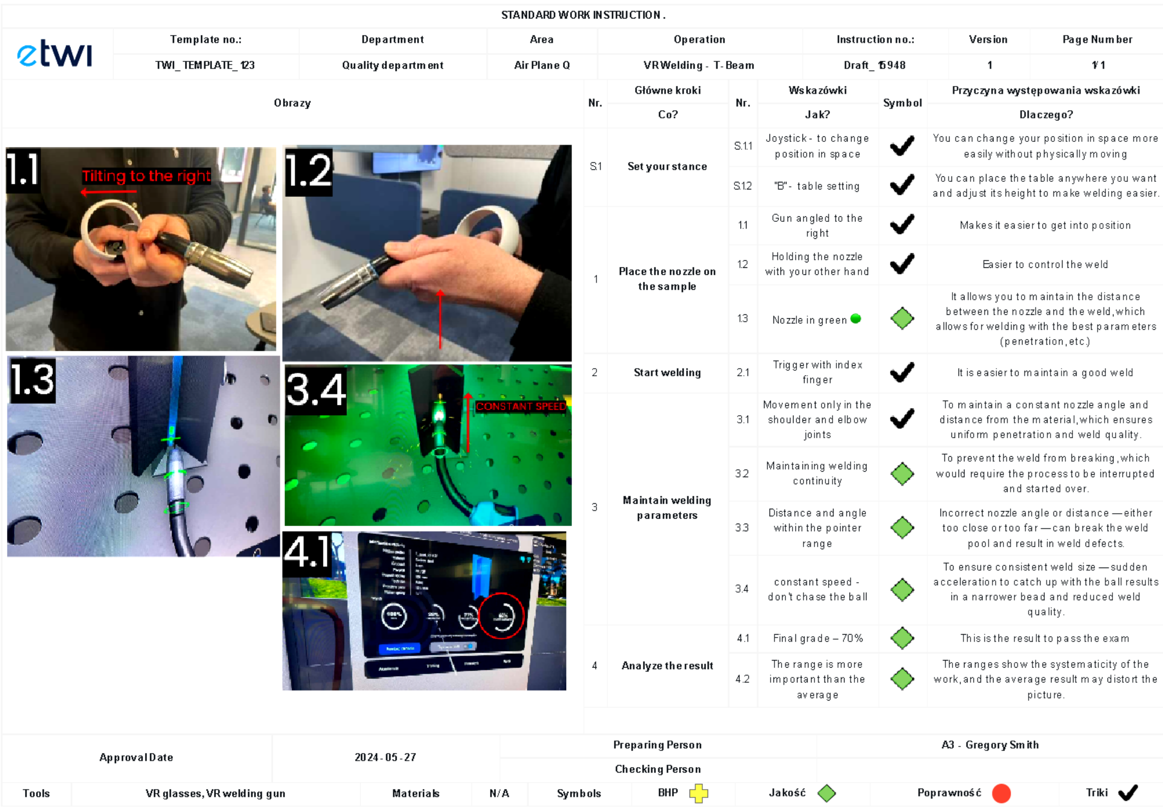
3. Survey Instrument

After the sessions, participants completed a Likert-scale questionnaire. The key statement was: "The training felt realistic compared to actual welding". Ratings ranged from 1 (Strongly Disagree) to 5 (Strongly Agree). Since each participant evaluated both the VR and AR training systems, the two sets of scores are dependent. Therefore, a paired samples t-test (dependent samples t-test) was applied to assess whether the perceived realism differed significantly between the two modalities.

4. Instructional Design

To maximize the effectiveness of both the VR and AR training platforms, we integrated a structured instructional design based on the Training Within Industry (TWI) Job Instruction (JI) method. TWI JI is a proven methodology dating back to the 1940s that emphasizes breaking down jobs into well-defined steps, important key points, and rationale reasons in order to train workers quickly and consistently (Misiurek, Misiurek, 2017). This approach was originally developed to rapidly upskill industrial workers during World War II, and it remains highly relevant for training in complex or dangerous tasks like welding (Wrona, Graupp, 2006).

We created a step-by-step welding instruction guide following TWI principles for a basic welding task for VR welding operation (Figure 3) and AR welding operation (Figure 4). These instructions were then embedded into the training systems: in the VR simulator, a tutorial mode leads the trainee through each step with prompts and highlights. In the AR system, instructions can be shown on the heads-up display – for instance, an arrow might appear on the workpiece indicating where to start. In addition, a trainer in the lab can use the TWI guide as a lesson plan when supervising trainees on either system, to ensure consistent messaging.



STANDARD WORK INSTRUCTION .

Template no.:	Department	Area	Operation	Instruction no.:	Version	Page Number
TWI_ TEMPLATE_ 123	Quality department	Air Plane Q	VR Welding - T- Beam	Draft_ 15948	1	1/1

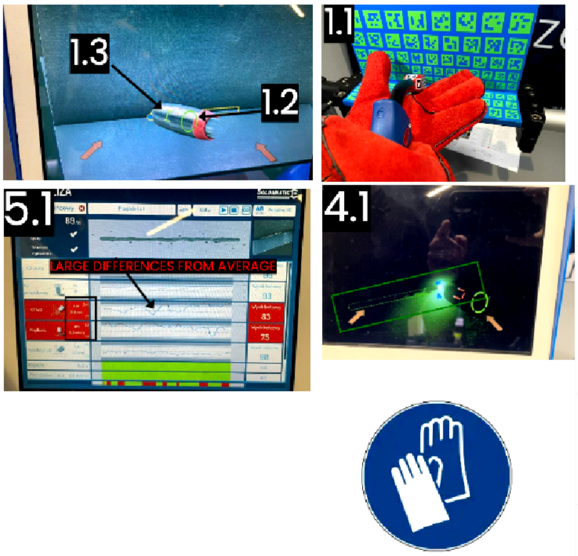
Nr.	Główne kroki Co?	Nr.	Wskazówki Jak?	Symbol	Przyczyna występowania wskazówki Dlaczego?
S1	Set your stance	S.1.1	Joystick - to change position in space	✓	You can change your position in space more easily without physically moving
		S.1.2	"B"- table setting	✓	You can place the table anywhere you want and adjust its height to make welding easier.
1	Place the nozzle on the sample	1.1	Gun angled to the right	✓	Makes it easier to get into position
		1.2	Holding the nozzle with your other hand	✓	Easier to control the weld
		1.3	Nozzle in green	◆	It allows you to maintain the distance between the nozzle and the weld, which allows for welding with the best parameters (penetration, etc.)
2	Start welding	2.1	Trigger with index finger	✓	It is easier to maintain a good weld
3	Maintain welding parameters	3.1	Movement only in the shoulder and elbow joints	✓	To maintain a constant nozzle angle and distance from the material, which ensures uniform penetration and weld quality.
		3.2	Maintaining welding continuity	◆	To prevent the weld from breaking, which would require the process to be interrupted and started over.
		3.3	Distance and angle within the pointer range	◆	Incorrect nozzle angle or distance — either too close or too far — can break the weld pool and result in weld defects.
		3.4	constant speed - don't chase the ball	◆	To ensure consistent weld size — sudden acceleration to catch up with the ball results in a narrower bead and reduced weld quality.
4	Analyze the result	4.1	Final grade – 70%	◆	This is the result to pass the exam
		4.2	The range is more important than the average	◆	The ranges show the systematicity of the work, and the average result may distort the picture.

Approval Date	2024-05-27	Preparing Person	A3 - Gregory Smith						
		Checking Person							
Tools	VR glasses, VR welding gun	Materials	N/A	Symbols	BHP	Jakość ◆	Poprawność	Triki ✓	

Figure 3. Work instruction for VR welding operation.

Source: Authors' own creation.

STANDARD WORK INSTRUCTION .							
ɛtwi	Template no.:	Department	Area	Operation	Instruction no.:	Version	Page Number
	TWI_ TEMPLATE_ 123	Quality department	Air Plane Q	AR Welding - T-Beam	Draft_ 15951	1	1/1



Obrazy	Nr.	Główne kroki Co?	Nr.	Wskazówki Jak?	Symbol	Przyczyna występowania wskazówki Dlaczego?
	S1	Get ready to weld	S1.1	Welding gloves		To reflect the real welding process as much as possible.
	1	Adjust the tip of the welding gun	1.1	Placing the nozzle on your hand	✔	It will be easier to weld if you have the nozzle on your hand - you will move your hand along the edge.
			1.2	O = Angle - > 45 degrees		The green circle indicates a 45 degree slope because we are making one weld to cover the entire angle of the T-beam.
			1.3	H = Distance - > 8-12mm		To ensure proper weld coverage — too much distance results in insufficient filler material, while too little leads to excess weld metal and potential overlap.
	2	Start welding (red button)	-	-	-	-
	3	Maintain welding parameters (Kąt O | Odległość H)	3.1	Wrist and elbow angle - fixed	✔	This will make it easier to maintain the welding angle, distance and speed.
			3.2	Continuous weld - > blue arrow		Interrupting the welding process leads to discontinuities in the weld, significantly reducing its strength and overall quality.
			3.3	Welding speed about 20-35 cm/min		Welding too quickly can break the weld pool, causing discontinuities and requiring the task to be restarted.
	4	Finish welding	4.1	Releasing the trigger at the end of the training section (green area)		To avoid welding outside the area marked with a green dashed line.
			4.2	Cancel Confirm exercise		To obtain the weld parameters and analyze them.
	5	Check welding parameters	5.1	Ciągłość wyniku ważniejsza od średniej		Czasami średnia może być ok, ale wynik w trakcie skacze i to jest oceniane nagatywnie. Spoina nie jest w pełni pokryta.

Approval Date	2024-08-20	Preparing Person	A3 - Gregory Smith
		Checking Person	

Tools	NA	Materials	NA	Symbols	BHP	Jakość	Poprawność	Triki ✔

Figure 4. Work instruction for AR welding operation.

Source: Authors' own creation.

The use of TWI JI brings a formalized pedagogy to VR/AR training, which might otherwise be used in an ad-hoc way (Dinero, 2011). By standardizing the training procedure, we aimed to eliminate any ambiguity for the trainees – each technology delivers the same fundamental instruction content (Misiurek, 2016). The TWI method is well-known for its ability to improve workplace safety and product quality through better training. Its mantra is "If the worker hasn't learned, the instructor hasn't taught," emphasizing instructor responsibility in skill transfer. In a study on construction industry safety, Misiurek and Misiurek (2017) applied TWI-based training and found it significantly reduced human errors contributing to accidents. They note that the TWI program focuses on improving employees' skills to perfect their work rather than simply raising productivity – a philosophy that aligns closely with welding training, where doing the job correctly and safely is the top priority.

By using a Job Instruction breakdown for welding, we ensure that trainees not only know what to do, but why each step is important (for example, why a certain travel speed is necessary to avoid weld defects, or why eye protection must be worn even in simulations). Even in the virtual environment, safety protocols were reinforced – the VR simulation, for instance, requires the trainee to virtually "put on" safety gear before welding (simulated via an equipment checklist), and the AR trainer likewise begins each session reminding about proper helmet use and ventilation (even though no actual fumes are produced, the habit is instilled). Such elements reflect the TWI philosophy of building correct habits and awareness.

By explicitly applying the TWI Job Instruction method, our training program seeks to eliminate variability in training quality between VR and AR. Both systems convey the same "one best way" to perform the weld, ensuring that any differences in outcomes between VR and AR can be attributed to the medium (e.g., the presence of physical cues in AR) rather than differences in instructional content. This strengthens the fairness of our VR-vs-AR comparison.

Results

AR received an average realism score of 4.13/5. VR received 2.55/5. The comparison of these scores is illustrated in Figure 5. The difference of 1.58 points was statistically significant ($p < 0.001$). Participants praised AR for physical realism: real tools, spatial orientation, depth perception, and tactile feedback. In AR, users could rest their hands, brace against surfaces, and view the weld through a helmet, replicating actual welding postures. an average realism score of 4.13/5. VR received 2.55/5. The difference of 1.58 points was statistically significant ($p < 0.001$). Participants praised AR for physical realism: real tools, spatial orientation, depth perception, and tactile feedback. In AR, users could rest their hands, brace against surfaces, and view the weld through a helmet, replicating actual welding postures.

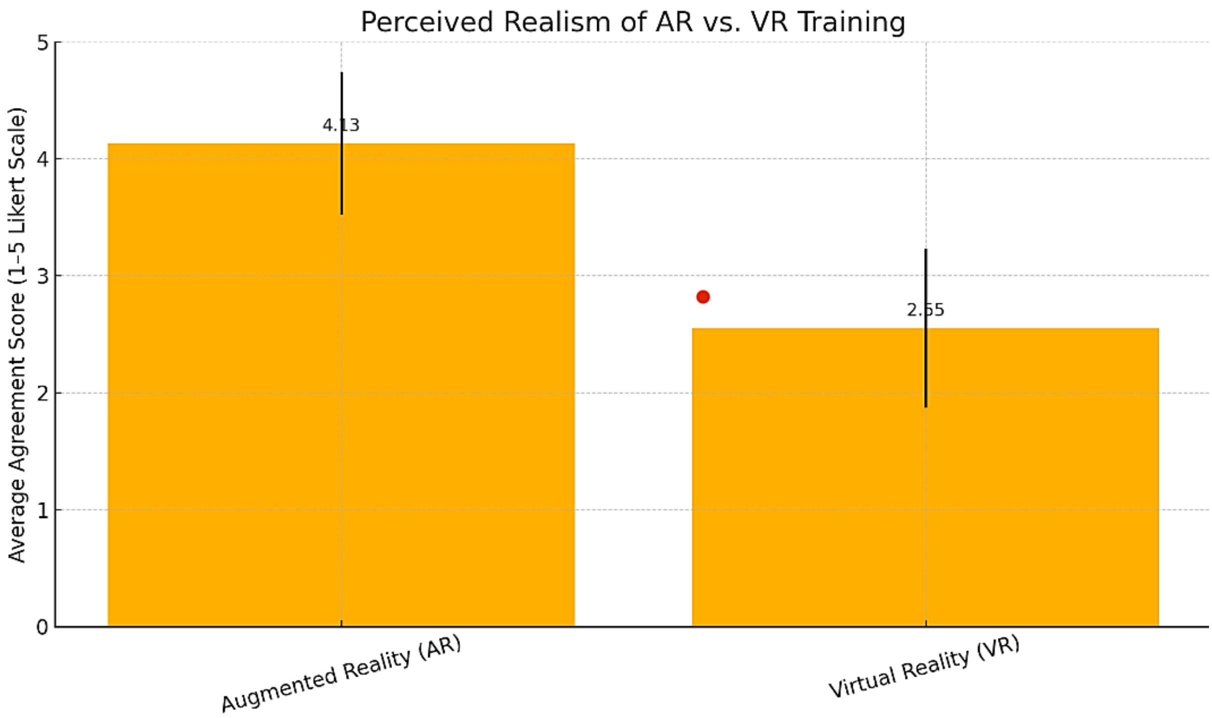


Figure 5. Comparison of the average ratings for VR and AR realism rating.

Source: Authors' own creation.

In contrast, VR was described as immersive but less authentic. Participants noted the absence of real resistance and reference points. Some attempted to lean on virtual tables and were surprised by the lack of feedback. VR's visuals, while clear, lacked the blinding arc brightness of real welding. Simulated audio and visual cues felt more like a training video game. Nevertheless, VR was valued for novice instruction. Participants appreciated its safety, repeatability, and guided practice. It allowed them to repeat fundamental techniques (e.g. torch angle, arc length) in a controlled space (Mozzoni et al., 2020; Roundtable Learning, 2023). These findings align with prior research suggesting that AR better supports skill transfer through physical fidelity and contextual interaction (Chan et al., 2022; Ai et al., 2024).

Discussion

It is worth noting that these ratings are subjective and pertain to perceived realism, which we use as a proxy for potential training effectiveness – the assumption being that training which feels more like real work will better prepare the trainee. We did not measure actual welding skill improvement in this survey – that is, we did not have participants perform real welds after training to assess skill transfer quantitatively. However, literature suggests a strong correlation between simulation realism and skill transfer in psychomotor tasks. Chan et al. (2022) emphasize that VR/AR welding trainers should mimic real-world welding conditions closely to effectively build psychomotor skills. Our findings align with that view: the AR system's physical interaction (real torch, real posture) likely contributed to a higher sense of realism and thus may yield better skill transfer.

Participants' comments provided insight into why AR felt more authentic. Many welders highlighted the importance of depth perception and hand-eye coordination with actual objects. In AR, they could physically touch the workpiece with the torch (the torch had an inert tip), and this tactile contact is exactly what they do to maintain arc length in reality (resting the cup or using distance feel). In VR, by contrast, if they tried to prop their hand on a table or lean on the workbench for stability, they found nothing solid (some actually tried and were surprised when their hand "went through" the virtual table). This lack of tangible reference points in VR was disorienting for some. Also, in AR they wore an actual welding helmet with the AR visor, which mimicked the constrained view through a real welding filter, whereas in VR the view was broader and not exactly like looking through a welding mask.

Furthermore, lighting and spatial awareness differed: AR trainees worked in the actual room lighting (with the augmented arc appearing bright), allowing their eyes to behave normally; VR had to simulate the lighting and some noted it wasn't as blinding as a true weld (to avoid discomfort, VR often tones down the brightness). Welders are used to a certain way the arc light affects their vision, so AR's handling of that (since it overlays a realistic glare effect) impressed them as more true-to-life. Despite AR's clear advantage in realism, our survey also underscored some positive aspects of VR. A number of participants acknowledged that VR would be excellent for initial practice and training novices.

In summary, the survey results strongly favored AR over VR in terms of experiential realism for welding training. This finding is consistent with prior observations in other domains: for example, Ai et al. (2024) found AR better suited than VR when actual body coordination was important, due to less simulator sickness and better user comfort. Similarly, in maintenance training, researchers have reported shorter task completion times and higher accuracy with AR instruction compared to screen-based or VR training (Liu et al., 2022). Our study adds specific evidence from the welding domain: experienced practitioners clearly recognize the added value of AR in replicating the feel of welding.

Conclusions

This study compared Virtual Reality (VR) and Augmented Reality (AR) in welding training, focusing on how realistically each method replicates real-world conditions. Welding is a high-risk process, traditionally requiring supervised hands-on instruction (Mozzoni et al., 2020; Pirvu et al., 2024). VR and AR offer safer alternatives by eliminating exposure to actual hazards (Pribadi et al., 2024). Our survey of 40 certified welders revealed a clear preference for AR, which achieved a realism rating of 4.13/5, compared to VR's 2.55/5 – a statistically significant difference. Respondents cited AR's use of real tools, physical posture, and tactile interaction as key factors that enhanced its realism (Alfaro-Viquez et al., 2025; Chan et al., 2022). In contrast, VR's lack of haptic feedback and physical reference points made it feel less authentic, although its safety and guided practice features were appreciated. Both systems have complementary strengths: VR excels in early-stage training, allowing for unlimited repetition and controlled environments; AR supports skill transfer through physical fidelity and context. Organizations should consider combining both approaches—starting novices in VR, then transitioning them to AR.

Future research should include quantitative skill transfer assessments and explore innovations like haptic VR feedback and multi-user AR systems. Recent findings suggest AR can reduce training costs without compromising effectiveness (Michalak et al., 2024). AR proved more realistic and effective for experienced welders, while VR remains valuable for foundational learning. Their integration—supported by structured methods like TWI—represents a forward-looking model for industrial skills training in the era of Industry 4.0 and 5.0 (Alfaro-Viquez et al., 2025).

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