Towards Modeling of Virtual Reality Welding Simulators to Promote Accessible and Scalable Training

Ananya Ipsita
School of Mechanical Engineering,
Purdue University, USA
aipsita@purdue.edu

Levi Erickson
School of Mechanical Engineering,
Purdue University, USA
ericks44@purdue.edu

Yangzi Dong
School of Mechanical Engineering,
Purdue University, USA
dong330@purdue.edu

Joey Huang
School of Information and Computer Sciences, University of California, Irvine, USA
chujenh@uci.edu

Alexa K Bushinski
Department of Psychological Sciences,
Purdue University, USA
abushins@purdue.edu

Sraven Saradhi
School of Mechanical Engineering,
Purdue University, USA
ssaradhi@purdue.edu

Ana M Villanueva
School of Mechanical Engineering,
Purdue University, USA
villana@purdue.edu

Kylie A Peppler
School of Information and Computer Sciences, University of California, Irvine, USA
kpeppler@uci.edu

Thomas S Redick
Department of Psychological Sciences,
Purdue University, USA
tredick@purdue.edu

Karthik Ramani
School of Mechanical Engineering,
Purdue University, USA
ramani@purdue.edu

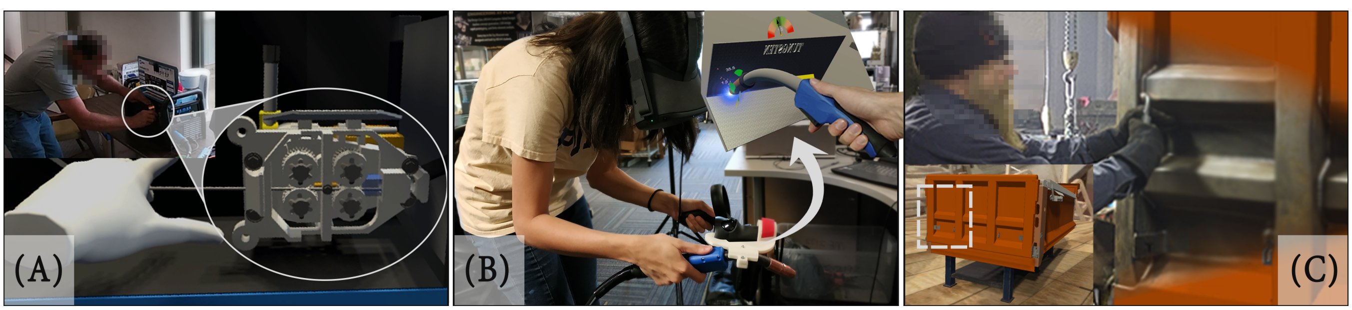

Figure 1: A low-cost Welding Simulator to improve the availability of welding training. (from left to right) (A) Excerpt from the welding setup and maintenance module showing real-world significance. (B) An alternative to replace Oculus controller from user's hands with a real welding gun. (C) Truck tailgate welding demonstrating personalization of the training environment.

ABSTRACT

The US manufacturing industry is currently facing a welding workforce shortage which is largely due to inadequacy of widespread welding training. To address this challenge, we present a Virtual Reality (VR)-based training system aimed at transforming state-of-the-art-welding simulations and in-person instruction into a widely accessible and engaging platform. We applied backward design principles to design a low-cost welding simulator in the form of modularized units through active consulting with welding training experts. Using a minimum viable prototype, we conducted a user study with 24 novices to test the system's usability. Our findings show (1) greater effectiveness of the system in transferring skills to real-world environments as compared to accessible video-based alternatives and, (2) the visuo-haptic guidance during virtual welding enhances performance and provides a realistic learning experience to users. Using the solution, we expect inexperienced users to achieve competencies faster and be better prepared to enter actual work environments.

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CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; **Interaction paradigms**; **Virtual reality**; • **Applied computing → Education**; **Interactive learning environments**;

KEYWORDS

Virtual Reality, Virtual Reality Welding Simulators, Welding, Manufacturing, Backward design, Virtual Reality Training

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1 INTRODUCTION

With the current resurgence in the US manufacturing industry, and experienced welders advancing and/or retiring at an early age, there is presently a substantial deficit in skilled welders. The American Welding Society (AWS) [82] estimates the shortage will be as much as 400,000 welding operators in the industry by 2024 [95]. Manufacturers are even having trouble hiring entry-level positions that do not require expertise [96]. Conventional welding training methods which include a mix of classroom instruction involving PowerPoint slides, video demonstrations and paper-based lecture notes, and workshops including instructor guided training and live practice sessions [68, 76] are unable to meet this demand due to high-cost and time, geographic constraints, and rigid scheduling [53]. Additionally, during training, students use filler metal, gas, and other consumables that increase costs as well as constrain equipment availability, thereby limiting the number of students that can be trained at the same time. The instructor's time also comes at a high cost which further limits the scaling of existing training methods. Therefore there arises a necessity to introduce more accessible and scalable methods of training to enable faster skilling of welders.

Previous works have highlighted the learn-by-doing approach provided by VR platforms when constraints such as machine availability, safety, time, or cost prevent the use of real environments [20, 28, 34, 48, 61]. We chose VR over other 2D accessible methods such as paper, web or video content due to its capability to provide in-situ spatial and embodied interactions for enabling hands-on experience for novices. Moreover, VR has been found effective in improving knowledge acquisition, retention and self-efficacy, and reducing error rate while enhancing user satisfaction as compared to these 2D alternatives [1, 13]. Past studies have also demonstrated enhanced learning rates and skills improvement (implying greater engagement, interest, and motivation) as a result of the induced sense of immersion and presence in such 'risk-free' virtual environments [13]. In addition, extra cues in the form of visual, auditory, or haptic feedback can facilitate learning of the task and allow simulating the task in a flexible way to adapt it to users' needs and training goals [20, 28]. Considering these advantages of VR, our work is focused on designing cost-effective educational applications for the welding industry with a clear orientation toward the final outcomes of the learning experience.

VR simulators for welding [22, 78] have gained popularity in recent decades and have been integrated into in-person training curricula. These simulators provide hands-on practice for learners to improve the necessary psycho-motor skills. However, the majority of them have limited content and concentrated mostly on virtual simulations of localized virtual welding equipment and empirically assisted activities. Thus, these VR simulators typically require instructors to supervise and guide the novices, and lack a holistic approach to train novices about welding concepts at scale. Moreover, the high-costs of installation, placement constraints on the environment, and sophisticated hardware calibration restrict access of these facilities for novices, and therefore they were not suitable to overcome the welder shortage in effect today. Keeping these issues in mind, we have made an attempt to design structured content into a widely accessible platform in order to improve the accessibility of training.

We present ***VRWeldLearner***, a system design which systematically breaks down welding, and provides a taxonomy that encompasses learning modules achieved through a set of design guidelines in VR. By adopting the backward design approaches [58], we identified the desired learning outcomes first by collaborating with welding training experts, subsequently worked "backwards" from the desired performance to identifying the assessment strategies, and finally designing the learning activities to meet the goal. As a part of the learning content, we provide an engaging and low-cost alternative for visuo-haptic guidance associated with carrying the physical welding gun (WG) while performing virtual simulations (Figure 1B). By using 360-degree video rendering, the system can transfer worksites into a virtual platform for helping in the transition to manufacturing workplaces and enable personalization of the training environment in VR (Figure 1C). We implement a training tool in the form of a minimum viable prototype comprising three units from the whole (Figure 1A) and conduct a pilot study with 3 welding experts to test its validity. Then, we perform the user study with 24 novice welders to evaluate the usability of the training tool, and demonstrate the user engagement and effectiveness of the system to transfer skills into the real-world environment. Through the findings from the study, we want to answer the following research questions:

- To what extent does the use of interactive video tutorials and guided activities inside VR enhance the student's performance and user experiences as compared to 2D video-based training alternatives?
- To what extent can we validate the choice of using the welding gun instead of the Oculus controllers during virtual welding?

Thus, the contributions are as follows:

- **A design and learning rationale and taxonomy** extracted using the backward design approach in learning sciences [98] and through discussion with welding training experts that shows what to consider while designing an effective training system for novice welders;
- **A design framework** encompassing structured learning modules to achieve a low-cost and widely scalable virtual Metal Inert Gas (MIG) welding training; and

- **The user study and evaluation** results to validate the system's usability using a minimum viable prototype, evaluate the performance of the proposed alternative for visuo-haptic guidance during virtual welding, and understand the impact of visuo-haptic perception in VR towards the development of psycho-motor skills in welding for novices.

We hope that this work provides insights to the HCI community to better understand how to leverage VR systems in training complex processes.

2 RELATED WORK

VR in welding training: Huang et al. [35] verified the effectiveness of VR technology to assist the development of VR welding courses in welding practice teaching. Past works have developed VR-based welding simulators to enable the user to set-up, execute and validate the MIG-welding process in a same and immersive environment [29, 56, 92, 97, 100]. Virtual simulators developed by Yunus et al. [101] have shown considerable amelioration in the user's skills.

Commercial systems like Lincoln Electric VRTEX 360 [22], Soldamatic [78], Arc+ Welding Simulator [15], Fronius [27], guideWELD® [72] and CS Wave [12] enable welders to be trained faster. Consequently, faculty have reported improved performance while supervising students' welds in terms of familiarity and the quality of welds [69]. However, these simulators provide limited content in that they focus primarily on the simulation of weld-bead geometry on welding joints. Based on the interviews with welding training experts, it was found that novices often enter the workplace with a gap in knowledge related to the setup and maintenance of welding equipment. This information is missing from the limited content provided by commercial VR simulators. For example, some activities that they usually have trouble with include how to change a wire-spool, drive-roll maintenance, and/or liner replacement. To address these issues, we designed a welding curriculum in VR that includes an end-to-end learning progression of content and exercises to aid the novices in learning these core skills alongside welding simulations through guided activities.

Use of visuo-haptic perception for virtual welding: Passive haptic devices emulating the real instruments and their properties such as mass and shape have proven useful to provide spatial presence [5, 46], skills [46, 52] and immerse users into the virtual world [47]. Such specialized input devices can assist trainees in acclimating to novel hardware and are believed to produce superior results since they can mimic the natural performance of activities and increase fidelity [34]. The visuo-haptic feedback from holding the real WG accompanied by VR visuals can provide the illusion of sparks coming out of a physical-virtual WG while providing the necessary kinesthetic information related to posture and perception of hands within space along with the associated tactile memory. The usage of visuo-haptic guidance associated with holding a WG in developing the motor skills required for welding has been demonstrated by previous works [15, 97, 100]. Many of them utilize high-cost sensors situated in the environment that help in determining the position and orientation of the WG. However, usability of these sensors is limited due to high-cost, calibration requirements, and placement constraints [15, 24]. Related works have enabled the usage of visuo-haptic guidance in virtual welding through registration of the position of the electrode through various methods such as electromagnetic tracking [44], marker tracking [45], optical tracking [97], and single-camera vision measurement using a PS Eye camera and inertial sensors [100]. Fast et al. [24] created a virtual welding training system in which the motion of WG and welder's head (view) is tracked using a commercial ultrasonic/inertial 6 DOF tracking system. However, the setup costs and difficulties associated with using such systems are very high, restricting their usage for novice welders and for small-to-medium businesses, especially those in low-income and rural areas. To address the tracking need without high equipment costs, the virtual WG was rendered in VR by tracking the 6-DOF of the Oculus Controllers (OC) and attaching it to the WG using a 3D-printed mount.

Adoption of Virtual Reality for creating effective learning environments: VR training environments are characterized with representational fidelity, embodied interaction, support of psychological sense of presence and immersion, and have been shown to be beneficial in pedagogical contexts [18, 55, 89]. The sense of presence in these environments was found to keep learners motivated and involved in the learning process by facilitating focused and realistic interactions with learning materials and activities [13]. Situated learning was improved by simulating realistic contexts and providing contextualized learning activities, resulting in better performance transfer from the learning environment to the real-world setting [6]. While previous research has investigated the impact of these immersive technologies on student achievement, motivation, engagement, and immersion [34], there hasn't been much focus on the systematic integration of pedagogical concepts into the design of VR learning environments [65, 67]. To build effective learning environments using these immersive technologies, how the course material is aligned towards the targeted outcomes of the learning experience and presented to learners, are important factors that must be addressed during the curriculum planning and design of the course [16].

Meanwhile, only a few research studies looked at how to design instruction by first identifying the desired learning outcomes [36, 39, 40, 66, 80, 81, 83]. The backwards design principle was adopted by Hulme et. al. to re-design a driver training module that combines simulation, technology, and serious gaming as major components [36]. CiSE-ProS was created to teach cybersecurity principles in a virtual environment through immersive and embodied activities [80]. The training program helped undergraduate students with short and long term memories in playful and engaging ways. The instructors of four biology-related courses integrated Labster virtual labs into their courses by aligning the labs with the learning objectives of their courses and connecting the labs to their course assessments [66]. The labs were tested with 370 students in which the results revealed that virtual lab simulations helped at least 77 percent of the students in understanding the course ideas. Singh et. al. explored video immersion in VR to offer experiential learning environment to help meet the learning goals of simulation labs in biomedical engineering education [81]. Kannegiser et. al. designed and evaluated an augmented reality library orientation to increase students' comfort and confidence with the library and librarians [40]. iVR focused on designing instructional gaming materials specifically for nonformal STEM education learning environments by adopting design concepts for learning, game design, and language curriculum development [39].

Inspired by the prior works, our research aims to create an opportunity for welding novices to learn and practice welding related concepts and skills in a virtual setting by proposing an instructional approach through adherence to backward design principles [58, 98]. With this instructional design, the desired learning results of students are firstly identified, followed by the learning activities that can be guided toward those outcomes. The instructional methods are tailored to fit the students' learning context and experience in order for them to achieve the proficiency level needed to succeed during the performance assessments. Previous research has found that this design approach was meaningful [64], could accomplish the goals faster [42], helped students learn better than traditional lesson designs, and offered better learning motivation towards the learned lessons [71, 85].

3 TERMS AND DEFINITIONS

The following definitions will aid in the understanding of terminology used in this research work.

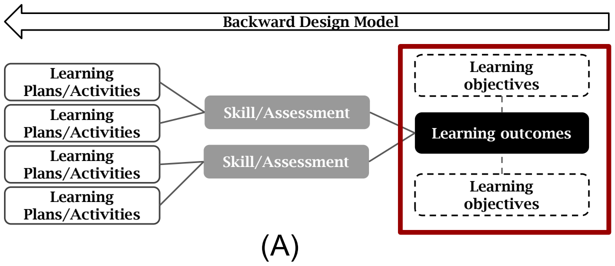
- *Skills* are the acquired abilities that facilitate the performance of activities that occur across jobs [99]. They work mostly subconsciously and can be split down into smaller, more manageable components called microskills.
- *Microskills* are the specific abilities, or the small segments of information or knowledge required to perform a task [91].
- *Learning outcomes* indicate the relevant objectives (e.g., established goals, desired understandings) that will be addressed by the system. These will be useful in determining what students will know (e.g., what critical knowledge and skills will be acquired) and what students will be able to do as a result of the knowledge and skill acquisition [2].
- *Learning objectives* are goals that target specific knowledge, skills, and dispositions taught in specific sections of a module [60].
- *Learning plan* is a description of how to design the learning experience and instructions to achieve the desired outcomes in learning [60].
- *Learning activity* can be defined as a specific interaction of learner(s) using specific tools and resources, orientated towards specific outcomes [17].
- *Learning module* is an organized collection of teaching materials consisting of behavioral objectives, a sequence of learning activities, and provisions for evaluation [75].
- *Visuo-haptic interaction* is achieved by the fusion of visual sense and the tactile information to extract, encode, and process spatial information from objects for the purpose of recognition and localisation [59].

4 SYSTEM DESIGN AND DEVELOPMENT

The involvement of dedicated human resources, and industrial-organizational psychology is considered important by researchers towards the design and development of industry-oriented gamified learning [34, 79]. Keeping this in consideration, we collaborated with three welding training experts from organizational training programs over a period of 5 months to gain insights on the theoretical perspectives of training, and closely align our rationale and approach to design the welding simulator. By incorporating the backward design model [58, 98] and approaches from learning sciences, we worked with the welding training experts to first identify the learning outcomes, and then backward designed the learning objectives and evaluation strategies for assessing learner's skills. Next, the instruction was designed to be imparted in form of self-directed learning modules with guided activities, practice sessions and assessments to enable learners gain proficiency in an organized manner. The model of backward design provides the principle of alignment in learning modules in which learning objectives, instruction, and assessment are aligned to each other to develop learning activities that fulfil derived learning outcomes as shown in Figure 2A. The system design and development of learning modules for the MIG-welding simulator were carried out in iterative phases as described below.

4.1 Discussion with welding training experts

We collaborated with the welding training experts with support from National Science Foundation (NSF) (see Acknowledgements for details). The training organizations are accredited by the state of Indiana in the US, with the training experts having taught welding for at least 10 years, and been actively engaged in the welding industry in various capacities over the last decade. The researchers introduced the topic of accessible VR training simulators in welding to the experts as a means of reaching learning goals more quickly and on a larger scale. The experts' familiarity with new kinds of technology in welding educational training including AR and VR, favored the researchers when it came to discussing the technology's potential benefits with the experts. For instance, the experts have been utilizing Augmented Arc trainer [15] in their schools, and were supportive of the learning-by-doing approach provided by the new educational technology. Having the prospect of a cost effective simulator (in contrast to the $ 25k Augmented Arc trainer) was envisioned to have a potential impact on skilling welding workforce through increased accessibility. The discussions happened through video teleconferencing, in-person meetings, instant messaging, and mail exchanges. As part of the design iteration, we conducted 3 online and 11 in-person meetings with the experts, with correspondence primarily taking place between at least 1 expert (out of three) and 2 researchers at any point of time. Prior to the meetings, we shared the design workflow and learning content for the experts to review. The materials were sent in the form of text and graphic formats, including storyboards, and toward the end of the design iteration, the design prototypes in VR were also distributed to the experts to collect their feedback. To aid the experts during testing, VR headsets and related hardware were provided to the training experts, along with essential demos and guidance from the researchers. During the meetings, the experts addressed the researchers' comments, explained the welding topics, clarified questions asked verbally by the researchers as well as provided live demonstrations for relevant topics as needed. Notes were taken by the researchers during the conversations and all meetings were recorded for future reference. Finally, the researchers held internal



Learning Outcomes
· Practice proper safety regulations in a MIG-welding workspace
· Perform setup and maintenance operations in a MIG-Welding setting
· Develop muscle memory required for different welding joints in different position
· Decrease time for preparation for AWS certification exam, at reduced cost of training
· Be better prepared and confident to enter actual workplace setting

(B)

Figure 2: From left to right (A) Overview of the backward design model used in designing the content of VRWeldLearner, and (B) Learning outcomes as obtained through the discussion with welding training experts

meetings to compile the experts' comments into a spreadsheet to further refine the design and learning modules. In case of any confusion, the researchers reached out to the experts using any of the methods as described above.

From our discussion with experts, it was highlighted that the usage of VR simulators would lead to a cost effective solution for welding training. There is no need for consumables with the usage of these simulators, and users can practice when they want, where they want, and how much they want, until they master the concepts. We discussed the benefits of virtual simulators in welding training and requirements about the structure of the VR simulator with the training experts. Information was collected about the training content involved with basic MIG-welding training in the form of course syllabi, welding manuals [63], and textbooks [5, 9]. The concepts covered during the training were identified and ranked in order of complexity and time needed to master the required skills, e.g., easy topics including basic welding safety and equipment, followed by moderately complicated tasks involving machine setup and maintenance, followed by more sophisticated concepts such as welding joints, positions, procedures, and defects. Students are normally explained the easier concepts in class by using PowerPoint presentations and lecture notes [76]. Additional instructor-guided live or video demonstration of the step-by-step procedures is usually required for moderately complicated procedural tasks [68]. Students undergo intensive live practice sessions during workshops to obtain the required skills for more complicated welding tasks after being taught and demonstrated these concepts. Based on our discussion with experts and information obtained from relevant literature, we established and tracked four Key Performance Indicators (KPIs) that greatly affect the end quality of the weld [4, 9, 11, 37, 38, 94]. They are maintaining the proper (1) travel angle, (2) work angle, (3) travel speed, and (4) tip-to-work distance. As pointed out by experts, *"The visual and judgement standards relating to the key welding variables - angles of the torch, contact to work distance, travel speed are key skills to be a successful welder. Welding is multi-tasking, needing to practice [these] skills simultaneously. When we set learning objectives, we need to pay attention to setting the standards for multiple skills, and assess them individually and simultaneously. Visual feedback from virtual weld bead [should be provided to the learner] if performed correctly or not. It would help build muscle memory drastically in a short period of time."* The identified KPIs and their impact on welding are explained as below.

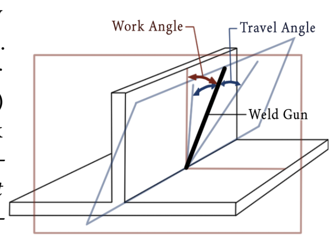


Figure 3: Angles of a weld

- The angles of the welding gun in reference to the weld joint and the travel direction are known as the *work angle* and *travel angle* respectively (Figure 3) [See: 4, pp. 63-65]. Proper penetration and bead formation can be ensured by using the correct angle. Undercut, partial/excessive penetration, incomplete fusion, and/or excessive spatters will occur if the angles are incorrect. *"The welder can change the weld bead as effectively by adjusting the gun angle as by adjusting the machine current settings."* [See: 38, p. 281]
- The rate at which the welding gun moves across the weld region is referred to as *travel speed*. *"Because the location of the arc inside the molten weld pool is important, the welding travel speed cannot exceed the ability of the arc to melt the base metal."* [See: 37, p. 30] When the speed is too high, the weld pool freezes too rapidly, trapping contaminants and gases. This tends to lead to poor penetration, incomplete fusion, porosity, and/or undercut. When the speed is too slow, the filler metal builds up too much, and result in overlap, burn through, excessive penetration and cracks. [See: 4, p. 222]
- *Tip-to-work distance* refers to the arc length, or the distance between the contact tip and the workpiece. *"Adjustments in this distance cause a change in the wire resistance and the resulting weld bead."* [See: 37, pp. 30-31] If the distance is too short it will not provide enough heat to melt the base metal, which can cause inadequate penetration, overlap and incomplete fusion. If the distance is too long, it will result in unstable welding arc, conversely leading to excessive penetration, undercut and spatter. [See: 4, p. 222]

Therefore, it was considered important to develop the skills needed to maintain these parameters within acceptable ranges as defined through industry standards. For example, the recommended ranges for different welding parameters i.e. work angle, travel angle, travel speed and distance for a Tee joint in horizontal position, as obtained using a compilation from several sources [4, 9], were noted to be 35-55 degrees, 10-20 degrees, 10-15 inches per minute, and 0.375-0.5 inches respectively *(Material : Mild Steel, Wire thickness : 1/8 inch)*. The learning outcomes were identified based on the feedback we received from the experts as shown in Figure 2B. With the use of VRWeldLearner, it was aimed to achieve faster preparation of learners towards AWS-certification [82] and faster lead times to enter actual workplace environments, obtained at a reduced cost of training. The learner can build the muscle memory and psychomotor skills necessary to perform welding related operations adjusting to industry specifications as required. The learner can understand what safety regulations to follow in an actual workplace setting and be able to perform the set up and maintenance activities on their own. Finally, the learner can be confident to enter workplace settings having been accustomed to the look-and-feel of similar environments in the virtual setup. After identifying the learning outcomes, the learning objectives and assessment strategies for the welding simulator were developed as shown in Table 1.

The following design goals were identified with an aim to make the system accessible to novices and provide an enjoyable and realistic experience while equipping them with necessary skills:

Accessibility: Previous virtual simulators [15, 22], such as those mentioned in the Related Work section, use highly sophisticated hardware and are costly. In contrast, complexity of the hardware and calibration requirements in our system is kept low. The system needs Oculus Head Mounted Display (HMD), the choice being the result of comparatively lower prices and easier configuration of Oculus as compared to other VR devices [13] and a WG, and thus avoids the usage of any complicated hardware. The setup cost is low involving the price of the Oculus HMD and the WG. Controls and interaction are intuitive, meaning no external support is required. The system is also accessible to users of various skill sets by eliminating the need for prior programming knowledge.

Realistic simulation and Real-time feedback: Inspired by techniques used in existing simulators [15, 22, 72] and from expert feedback, it was realized that renderings, animations, sound, and visual feedback associated with weld-bead formation should provide a similar sensation to real welding. Often, when a novice begins welding for the first time, they are 'gun shy.' The bright lights and loud sounds cause them to stutter because they are unexpected. Exposing users to these sensations in VR raises their KPIs right out the gate in real-world performance. Within VR, the KPI's identified as work angle, travel angle, travel speed, and contact to work distance are displayed to give a better understanding of how to control them in a desirable manner. During a demonstration using Augmented Arc trainer [15], experts mentioned, *"Visual feedback, as it applies to being in the correct position and speed, is critical. Show the [KPI] deviations [using markers,] similar to the Miller machine. If you go too far away or too close, the color [of the linear markers] changes to red. The circle [markers] keeps track of the angles, like when you move your hand down, or go right and come back in. Stay with the blue arrows, that's your travel speed. If you stay consistent, that's good. [Also] Provide a feedback on your weld after a weld is finished, grade percentage-wise how you did."* The geometry of the weld-bead can help to indicate if the KPIs were hit accurately. This geometry along with KPI feedback can affirm the integrity of the weld to the novice, and then through repeated practice, helps to build muscle memory.

Structured and Progressive: We found that learning progression mirroring a traditional classroom or textbook setting works well not only to introduce the learning content, but also to familiarize the trainee to VR. For example, the *Safety: Personal Protective Equipment (PPE)* module was created, and through a simple identification exercise trainees can practice touching objects in VR before moving onto more complex interactions. Through this method, the complexity of learning content and VR scene can scale simultaneously.

Holistic: It is often found that training curriculum used in the existing virtual simulators [15, 22] is specifically designed for welding certification, which focuses primarily on the act of welding and excludes the skill sets related to safety, setup, and maintenance. However, knowledge about these topics is also very important to ensure welder's safety, machine maintenance, and that the welding process is done correctly. Therefore, the simulator must provide hands-on experience for both non-welding and welding curriculum.

Engagement: The importance of a physical WG for novice learning was considered crucial along with the real-time feedback associated with it. As pointed out by the experts, *"Touch is an important part of welding, with how you do on the [Augmented Arc] Miller machine. Pick up at the right angles [45°with the gooseneck] and slide the [virtual] welding gun more into the hand. Model the 3D welding gun as a replica of the real one."* We explore the engaging experience achieved using the real WG while performing virtual welding. In addition to providing realistic haptic experience, the system should provide real-time visual feedback to achieve correct positioning for the WG.

4.2 Learning Plans and Design Guidelines

As a first step for designing the learning content, we adopted an approach similar to Villanueva et. al. [91] for clustering the types of microskills that could be recognized in VR: (1) Perceptual, which refers to the time specific ability or knowledge designed to draw users' attention, and deliver and/or interpret sensory information [31, 32, 51, 86, 93]; (2) Cognitive, which refers to the time specific ability or knowledge to generate and collect information from the users' working memory to think in the abstract, reason, problem-solve, and comprehend [23, 70, 88]; (3) Motor, which refers to the time specific ability or knowledge to properly perform an operation or process and involves bodily movements [26, 54, 74]. Following the rationale, we backward framed the learning plans based on the type of microskills as shown in Table 2. Adhering to the learning plans, a set of design guidelines were developed to act as building blocks for developing the learning activities. The virtual learning activities were designed in the form of interactive video tutorials, guided activities, and task demonstrations to provide sufficient information to users to proceed correctly. Careful consideration has been taken to evaluate and check the users' performance, and provide feedback at necessary steps before moving onto the next sessions. Here, we explain the design guidelines that are then used for developing the learning modules.

Asset generation: CAD models for welding objects required for the development were either designed using CAD software or taken from an online repository. Material properties were added to the models to provide realistic appearance for better visualization

Module	Time (min)	Learning Objectives	Skill Assessment Criteria for Successful Completion	Design Guidelines (with examples in parentheses)
1	15	• Identify the safety related workstation equipment and their locations	• Identify the learning elements in the workspace (PPE, hazardous materials) • Answer the comprehensive Q&A correctly (PPE, workplace safety, hazards)	• Asset generation of learning elements (CAD for PPE, animation for sparks/fumes/fires) • Guided Activity to direct users (Graphical indicators for highlighting PPE) • Interactive Video Tutorial describing the key concepts (PPE, workplace safety, and hazards) • Comprehensive Q&A to evaluate understanding (Understanding PPE and safety) • Feedback for engagement (Color change of indicators, audio feedback after answer selection)
2	15	• Identify the basic welding equipment as well as their function and locations	• Identify MIG welding equipment and their parts in the workspace • Answer the comprehensive Q&A correctly (MIG welding equipment and their functions)	• Asset generation of learning elements (CAD asemblies for welding equipment and parts) • Guided Activity to direct users (Graphical indicator for highlighting welding equipment, embedded images showing functions) • Interactive Video Tutorial describing key concepts (types of welding equipment and functions) • Comprehensive Q&A to evaluate understanding (understanding welding equipment and functions) • Feedback for engagement (Color change of indicators, audio feedback after answer selection)
3	40	• Understand the welder setup process and complete the steps independently without prompts • Complete the wire and shielding gas cylinder change processes by using the correct tools and procedure • Manipulate tools with the right steps to complete contact tip maintenance	• Perform machine operations correctly (setup welding machine, wire change, shielding gas cylinder change) • Answer the comprehensive Q&A correctly (machine part and parameter specifications)	• Asset generation of learning elements (CAD assemblies and animation for tools) • Guided Activity to direct users (Graphical indicators for highlighting equipment parts and functions, object manipulation for performing tasks, prerecorded animations for machine functions) • Interactive Video Tutorial describing the operation and steps (Machine operations on setup and maintenance of welding equipment) • Comprehensive Q&A to evaluate understanding (understanding part and parameter specifications) • Feedback for engagement/realistic experience (Color change of indicators, audio feedback after answer selection, audio and animations for machine operations)
4	30	• Identify types (fillet and groove) and parts (root, toe, face, throat, leg, reinforcement) of a weld • Locate and identify different joint types (i.e., tee, butt, lap, corner, edge) and positions (i.e., horizontal, vertical, overhead) • Perform welding on different joints	• Identify the basic learning elements (types and parts of weld, welding joints, and positions) • Maintain KPIs are within acceptable ranges (for different welding joints and positions)	• Asset generation of learning elements (CAD for welding joints) • Guided Activity (Avatar demonstration of welding joints with appropriate KPIs) • Interactive Video Tutorial describing key concepts (types of weld, its parts, welding joints, and positions) • Comprehensive Q&A related to evaluate user understanding (types and parts of weld, Score evaluation for KPI parameters) • Feedback for muscle memory (Graphical feedback for KPI correction in welding joints)
5	15	• Perform setup and practice welding on a truck tailgate	• Identify the joint type combinations on the truck tailgate • Adjust the KPI values accordingly	• Asset generation of learning elements (CAD for truck tailgate) • Feedback for muscle memory (Graphical feedback for KPI correction) • Personalization of training environments for realistic experience (360-degree video embedding for factory locations)

Table 1: Learning objectives corresponding to the learning modules for the virtual content of the welding simulator

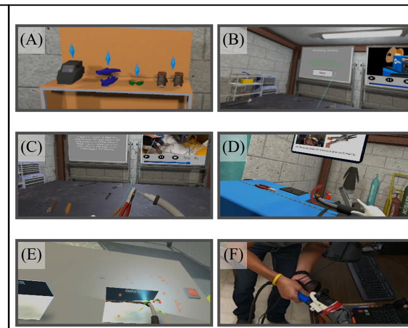
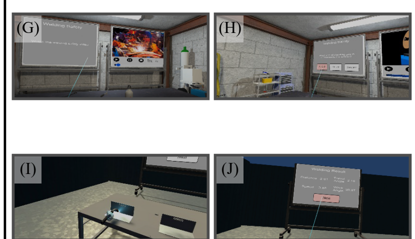
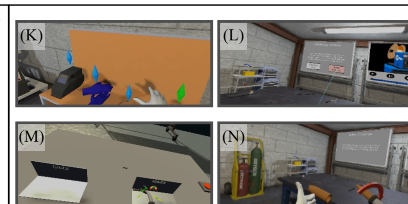
Microskills	Learning Plans	Content Design in VR	Screenshots examples from VR
Perceptual	• Bring users' attention to a particular object. • Teach spatial concepts in relation to self or objects • Get feedback on selection. • Provide parts, names, values, and functionality of objects • Teach directional language concepts such as "in", "out", "up", "down", "between", "left", "right" • Create body awareness to find position of body parts in relation to each other and their environment	• Virtual indicators to draw user's attention (A) • Auditory feedback after selecting objects of interest (B) • Highlight objects for attention (C) • Add embeddings (image/text/values/ graphical symbols) to objects for providing information/feedback (D, E) • Visual animations and sounds during virtual activity/process (E) • Use multisensory approach to deliver tactile, kinesthetic and visual information (e.g. Visuo-haptic perception of welding gun (F))	
Cognitive	• Teach about long-format concepts (principles and facts). • Explain abstract concepts. • Explain object/tool manipulation and assembly, • Teach procedural tasks involving sequence of activities • Provide examples on how to perform an activity. • Demonstrate the steps to complete a process. • Evaluate score for self assessment.	• Interactive Video Tutorials with Pause, play, rewind and stop features (G) • Breaking activities into steps by adding time markers and giving 1 or 2 directions at a time • Comprehensive Q&A for assessment of user's understanding of concepts (H) • Avatar demonstration to understand the tasks (e.g. how to hold a welding gun (I)) • Evaluation and score report at the end of performing an activity (J)	
Motor	• Guide user to perform object/tool manipulation and assembly, • Provide feedback for correction/task completion during virtual activity • Provide cues for adjusting limb movements, hand-eye-coordination	• Guided Activities for Object/Tool Manipulation and Assembly (N) • Selecting/Collecting objects of interest (K, L) • Response to feedback during Virtual activity/process (M) • Continue action till feedback is received (e.g. inserting drive rolls through the guide till audio feedback is received)	

Table 2: VR content design principles based on the Learning Plans aligned with the identified microskills

in the virtual scene. Animations were designed using graphical animation software and Unity.

Guided Activity: These include the types of affordances provided to enable users to perform tasks in the virtual scene. Some of these include manipulation of virtual objects (change position, orientation and scale; delete object), graphical indicators to direct the users, evaluation of users' understanding using assessments and selection of proper choices. Pre-recorded avatar demonstrations of proper techniques involved during complicated real-world tasks e.g., experts' hand trajectories for tee-joint are also used to display the actions before the user actually performs them in VR [14].

Interactive Video tutorials: Interactive videos presented in VR act as a virtual tutor to provide relevant information regarding fairly simple topics e.g., identifying PPEs, to moderately complicated procedural tasks e.g., how to perform welding wire change, in the context of the scene [77]. Interactivity mechanisms offered by such videos range from basic operations, i.e., stop, pause, traverse, and replay, to the inclusion of decision points for enabling guided hands-on and free exploration for learners inside VR, to intermittent quizzes that can engage them in making decisions. For example, while explaining the concepts of welding safety related to cylinders and compressed gases, the video is paused indicating the user to locate the gas cylinder and identify it's parts (e.g., cylinder cap, cylinder valve, valve outlet cap, etc.). Text, auditory, and/or visual cues are provided to help the user proceed in the correct direction. After the user performs the task successfully, the video is resumed. Use of such videos can help enhance understanding of the material, accelerate the process of skill acquisition while enhancing the student's learning experience at low cognitive costs [19].

Data Evaluation: Modules which require users to recall some information can be evaluated in a traditional method such as Q&A within VR, or through a comprehension exercise. For example, a user can be asked which shielding gas to use with the welding machine via Q&A, which can then be followed by a comprehension exercise where the correct cylinder must be selected from several options. This use of retrieval practice is an effective learning strategy for more durable long-term memory [41]. Moreover, data from

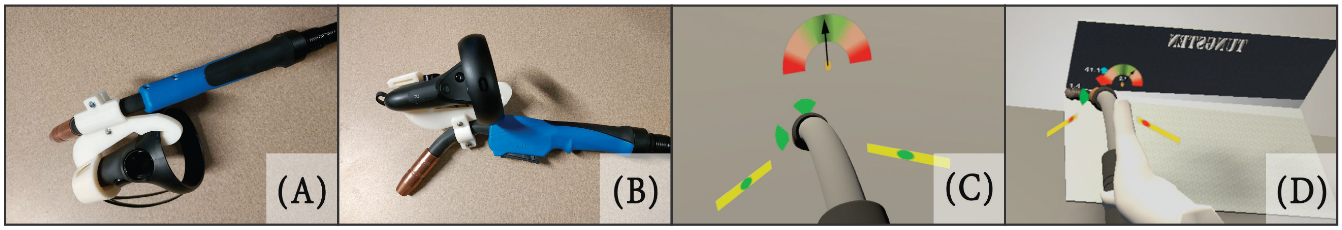


Figure 4: Design of the welding gun for feedback (from left to right) (A) top view of the welding gun attached with the 3D-mount, (B) side view of the welding gun, (C) Graphical design for real-time feedback in VR (Left and top arrows, the two lines, and the indicator arc provide feedback for the travel and work angles, distance, and the travel speed, respectively), (D) Screenshot showing real-time feedback while virtual welding.

hand movements can be recorded to show pauses or unnecessary movement to provide another area for analysis.

Feedback: Auditory and visual feedback are incorporated to provide users with real-time feedback about their performance, e.g., object markers turn green when a correct selection is made, and a chime rings when a guided instruction is completed, which can give the novice confidence about the progress. In addition, the feedback can make the learning experience more enjoyable.

- **Visuo-haptic guidance with a WG:** We expected that holding a WG instead of the OC would increase the fidelity of the scene and improve the user experience. Therefore, the OC was replaced from the user's hands with the real WG for providing the sense of touch which was expected to be crucial in building the necessary psycho-motor skills [94]. A 3D-mount was used to attach the OC to the WG as shown in Figure 4A,B. The design of the 3D-mount was influenced by [87], and the dimensions were modified to suit the requirements. The relative position of the WG with respect to the OC is fixed in the physical world, and thus the virtual WG is rendered in VR by using the continuous tracking of the OC (rendering frame rates same as refresh rate in OculusQuest^{TM} i.e. 72 Hz, and resolution 4128 * 2096) with an offset position and rotation as obtained from the CAD assembly. Real-time feedback for the positioning of the WG relative to the workpiece is shown using graphical symbols for the welding parameters such as travel angle, work angle, speed and distance. These symbols are demonstrated in Figure 4C. The left and top arrows, the two lines, and the indicator arc provide feedback for the travel and work angles, distance, and the travel speed, respectively, during the virtual welding. Acceptable ranges for the parameters are predefined in the application and the indicators are displayed in green when the parameters fall within the ranges. If not, appropriate indicators are displayed in red to inform the user to modify the position of the WG. A screenshot of the performance of the feedback system during the virtual welding is shown in Figure 4D.

Personalization of training environments: It was also suggested from experts that capturing employer specific training scenarios in the simulator could enhance the scope of personalization of training environments in VR. Therefore, 360-degree photo backgrounds were introduced to create virtual scenes reflecting real manufacturing environments. 360-degree videos were collected from factory locations, and rendered in VR to make the training scene as realistic as possible. With permission and the digital property from the company, the CAD models of their product could be placed in the scene to give high detail and intractability to the objects which are the focus of the scene. Mixing the CAD models of the product with the 360-degree background helps to give a sense of presence to the user [8], at the same time reducing the computational cost for realistic rendering of the scene [21]. Because most companies already keep the detailed CAD files required to create these scenes, they can be created for custom usage with relatively low effort. When a new employee is added to a manufacturing team, initial training is usually done off-floor so the trainee is not exposed to the hazards of the workplace or so that they don't interfere with production. For these reasons, new trainees can practice remotely in these scenes to ease the transition to the real environment and enter better prepared.

4.3 Learning Modules Design

The virtual learning content was designed in a structured format to help users learn the concepts of safety, machine setup, maintenance, and welding (Figure 5). We arranged the learning modules in a progressive manner (see section below) after studying the existing welding manuals [5, 63] and discussing with the experts. Modules 1, 2 and 3 introduce the non-welding content related to safety, welding equipment, and setup and maintenance respectively to novices and acts as an essential precursor to the welding training. Adding this content in VR results in a more rounded and full-fledged form of training for novices. Having been introduced to the tools and functions in the welding settings, novices can more confidently enter the welding training modules 4 and 5.

Module 1: Safety: The safety module involves identifying the PPEs that are required at worksites to prevent any kind of bodily hazards. This module contains interactive video tutorials with identification exercises for PPEs in the form of guided activities and assessment exercises to evaluate the users' understanding of the concepts.

Module 2: Welding Equipments: The welding equipment module is designed to give novices an overview of the commonly found equipment in a MIG-welding setup and their functions. This module contains interactive video tutorials with identification exercises

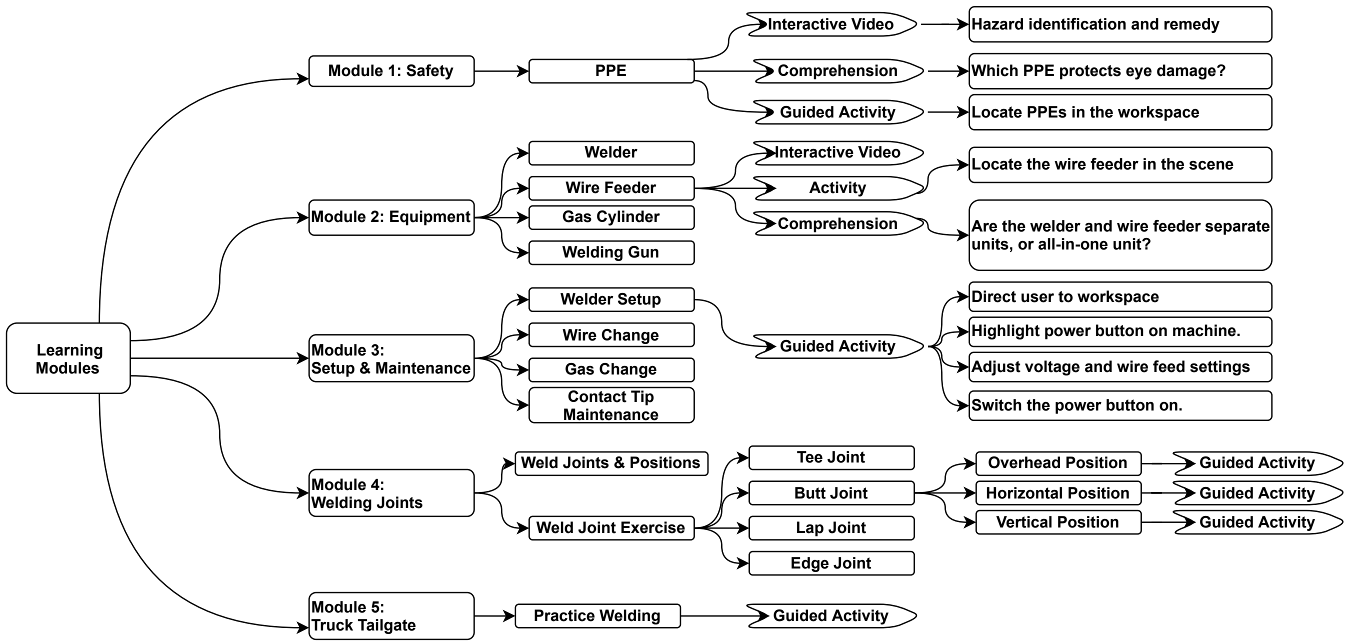


Figure 5: A breakdown of learning modules for the virtual content of the welding simulator

for welding equipment and assessment exercises to evaluate the users' understanding of the concepts.

Module 3: Setup and Maintenance: Welding setup and maintenance involve numerous spatial tasks like tool operations, bodily movements and hand-eye coordination. The activities included in this module are setting up a MIG welder, changing wire in the wire-feeder, changing shielding-gas cylinders, and contact-tip maintenance. The modules contain interactive video tutorials and guided activities to help users gain a hands-on experience of the operations in the virtual environment.

Module 4: Joints and Positions: Developing the psycho-motor skills for welding requires practice. Novices must understand the standard requirements for the welding parameters such as angles of the WG, distance, and speed to make a good weld. They should be able to relate the tips and tricks to various welding joints at different positions. The welding module is designed to help users understand and identify different joint types and positions, and perform welding while maintaining proper standards for the parameters on different joints. The modules contain guided demonstrations and provide exercises for users to practice welding activities.

Module 5: Truck Tailgate: Having gained an understanding about the welding joint types and positions, this module allows users to practice welding on a truck tailgate with the training scene being set using 360-degree videos collected from the production floor of the company that manufactures said tailgate.

5 USER TESTING AND EVALUATION:

In order to evaluate the accessibility, effectiveness, and engagement of the system as a whole, three lessons were selected to create in detail, as a minimum viable prototype for the user study. A detailed end-to-end approach of the design process used to develop the lessons based on the principles of the backward design model can be found in Table 3. First, PPE was introduced to acclimate the user to the scene and implement an interactive comprehension test. Second, the wire change lesson was used to test the user with a mildly complex activity through guided instructions. The welding wire change lesson was implemented in such a way that it could provide detailed information about the correct steps in sequence needed to perform a wire change on a Millermatic-210 welding machine with guided activities and interactive video tutorials. The steps in sequence involved in this lesson are:

(1) Remove nozzle from WG by rotating it counterclockwise.
(2) Remove contact-tip using pliers by rotating counterclockwise.
(3) Open cover of welding machine.
(4) Open tension.
(5) Cut bent wire.
(6) Feed wire through drive-rolls.
(7) Close the tension.
(8) Close the cover of welding machine.
(9) Turn on the power switch on welding machine.
(10) Press trigger to feed the wire through WG.
(11) Set wire to correct length.
(12) Reassemble the contact-tip by rotating clockwise.
(13) Reassemble the nozzle on WG by rotating clockwise.

Third, the weld-joint exercise lesson was actualized because it teaches the core skills of welding, and reduces the essence of high-cost welding simulations to its simplest form of taking input from the user and providing visuo-haptic feedback to the user to build muscle memory. In the weld-joint exercise, users were introduced

Learning Outcomes	Learning Objectives	Skill Identification for real welding	Skill Assessment Criteria
· Practice proper safety regulations in a MIG-welding workspace	· Understand need and proper usage of PPE associated with MIG welding · Learn about hazards involved in welding - electrical, fumes, fires/explosions	· Knowledge about PPE, workplace safety, hazards involved · Ability to identify PPE, hazardous materials in the workspace	· Identify the learning elements in the workspace (PPE, hazardous materials) · Answer the comprehensive Q&A correctly (PPE, workplace safety, hazards)
· Perform welding wire change in a welding machine	· Understand the step by step procedural instructions to change welding wire on a welding machine · Memorize the steps involved in sequence · Learn about different tools required for performing wire change on a welding machine and their usage · Learn about different parts of the welding machine, their locations and their functions	· Ability to perform wire change on a welding machine correctly · Knowledge about different parts of a welding machine, their locations and functions · Knowledge about different tools (e.g. pliers), their correct usage · Ability to identify correct tools required to perform wire change · Ability to identify components of welding machine, welding gun	· Perform machine operations correctly (wire change) · Answer the comprehensive Q&A correctly (machine part and parameter specifications)
· Develop muscle memory required for welding Tee joint in horizontal position	· Locate and identify joint type (Tee) and position (horizontal) · Understand the different KPIs (distance, travel angle, work angle, speed) and their specifications for welding Tee joint in horizontal position · Perform welding on a Tee joint in horizontal position	· Ability to identify Tee welding joint in horizontal position · Knowledge about the KPIs involved during welding · Knowledge about how to hold a welding gun while maintaining acceptable KPI values for Tee joint in horizontal position	· Maintain KPIs for contact to work distance, work angle, travel angle and speed within acceptable ranges for Tee joint in horizontal position

Learning Modules

Perceptual Microskills in VR	Cognitive Microskills in VR	Motor Microskills in VR	Learning Activities
· Ability to understand spatial commands (finding flammable objects from the table; locating PPEs and equipments in the workspace) · Perception of visual and auditory feedback before/after an activity has started/ended.	· Ability to obtain information (e.g. PPEs, workplace safety hazards, MIG equipments) from working memory during Q&A · Ability to group objects belonging to category of interest (e.g. PPEs)	· Body movement to perform activities (e.g. collect PPEs in the workspace) · Grasp and manipulation of virtual objects (e.g. removing flammable objects from the workbench)	**Lesson 1: Safety** · Interactive Video tutorial on basics of Safety · Collect Personal Protective Equipments in the virtual workspace (gloves, helmet, boots, safety glasses) · Remove the flammable liquid containers from the workbench · Locate the weldeing machine and gas cylinder. · Comprehensive Q&A: Are the power sources and wire feeder separate or all in one unit? Choices: Separate units, All in one unit · Comprehensive Q&A: What type of shielding gas is connected to the welder? Dropdown options: Ar-Co2, Helium, Oxygen
· Spatial relationships in relation to self or objects (e.g. plier and machine parts - large/small serrated holes for nozzle/contact-tip, cutter for wire) · Ability to understand spatial commands (e.g. cut the bent wire at the tip, insert the wire through the drive rolls) · Spatial awareness to find position of machine parts with respect to each other (e.g. Switch and cover on welding machine; nozzle, contact tip and trigger on the welding gun; tension and drive rolls on the wire feeder)	· Ability to finish task without skipping sections (e.g. assemble nozzle on the welding gun without missing the step of assembling the contact tip) · Ability to retain or recall information from information presented visually during the interactive video tutorials (e.g. Parts of the welding gun, Finding the welding pliers before beginning the welding wire change) · Ability to retain, remember and recall a sequence or pattern in a specific order (e.g. steps in sequence, press trigger till wire comes out of diffuser->Assemble contact tip->Assemble nozzle.) · Understand directional language concepts involved during the activity such as "clockwise", "anticlockwise", "through" (e.g. disassemble nozzle by rotating clockwise)	· Grasp and manipulation of virtual objects to perform discrete motor skills (e.g. switching the power button on/off) or continous motor skills (e.g. Pressing trigger continuously until wire comes out of the diffuser.) · Ability to use either hand for different functions (e.g. holding welding gun with one hand, and using plier to remove contact tip using the other hand) · Hand-eye coordination (e.g. during feeding the wire through the drive rolls) · Grasp and manipulation of virtual objects to perform fine motor skills (e.g. assembly/ disassembly of the welding gun, insert wire through the drive rolls) or gross motor skills (e.g. open/close the cover of welding machine)	**Lesson 2: Welding Wire Change** · Interactive Video tutorial on how to perform welding wire change on a welding machine with time markers at 19s, 40s, 57s, 64s, 79s · 19s, Remove the nozzle and contact tip on the welding gun. · 40s, Remove the cover of the welding machine. Adjust the tension (open) · 57s, Put a new spool of wire onto the spindle. Cut and remove the excess wire from the wire spool. Feed the wire through the dirive rolls after cutting the bent wire at the tip. Adjust the tension (close) · 64s, Turn on the welding machine. Close the cover of the welding machine. · 79s, Press the trigger to feed the wire through the gun cable until wire comes out of the diffuser. Cut excess wire. · 115s Reassemble the contact-tip and nozzle on the welding gun.
· Awareness of feeling of touch between user's hands and the real welding gun · Awareness of spatial concepts (judging the distance near or far, work angle left or right, travel angle inwards or outwards) · Quick, accurate or refined interpretations of visual information (from feedback during virtual welding)	· Gaining relevant information from charts (e.g. performance assessment after virtual welding) · Understand directional language concepts (e.g. "near", "far", "inwards", "outwards", "left", "right")	· Imitate expert's hand movement during expert demonstration · hand eye coordination to achieve the accurate KPIs during the virtual welding · grasp and manipulation of physical-virtual welding gun to perform virtual welding	**Lesson 3: Tee Joint, Horizontal Position** · Watch expert demonstration on how to hold a welding gun with correct hand poses · Understand the Tee joint and horizontal position · Practice virtual welding on Tee joint in horizontal position while maintaining acceptable KPIs · Perform self evaluation at the end of the activity

Table 3: Design and development of the lessons (PPE, welding wire change, Tee weld-joint) for the Minimum Viable Prototype using the backward design principles

to the feedback system and then asked to virtually weld the tee-joint in a horizontal position using both OC and the real WG. They were asked to maintain acceptable values for the KPIs associated with the virtual WG as indicated by the graphical symbols during virtual welding. To evaluate the system's usability, we conducted two studies, first the pilot study with 3 welding experts and then the user study with 24 welding novices. During the study session, the application was run on OculusQuest^{TM} tethered to a computer to provide control to the researchers to see and manipulate the scene in case of occurrence of any simulation errors. However, the application is capable of being deployed as a standalone version and has been tested without any differences in performance compared to the tethered version.

5.1 Pilot Study with Welding Experts:

5.1.1 ***Study Setup:*** The system was tested with 3 AWS-certified welding experts (3 Male) who were recruited from the training organization by word of mouth. However, they were not the same experts who were consulted for the system design, and were not familiar with the system. From the study, the system performance was evaluated through expert testing, and their feedback was collected about the potential of the system to be used as a training tool and necessary modifications to improve the system for the user study. Two users (Age=18-24, 25-34 years) had more than 5 years of welding experience, and the third user (Age=55-64 years) had more than 10 years of welding experience. The study took place in the training organization and was approved under the IRB protocols.

5.1.2 ***Study Procedure:*** VR equipment was provided to the experts before the study process began. Next a researcher explained the instructions verbally about the functions of physical buttons on the OC and virtual buttons in the system. The lessons described above (PPE, welding wire change, and weld-joint exercise) were tested with the expert users. The experts were asked to complete a 5-point Likert scale (*1=Strongly Disagree, 5=Strongly Agree*) based questionnaire survey after the testing was finished. Qualitative data was also obtained from a brief interview where they were verbally asked by a researcher about their experience with the system, potential of the system to be used in welding training, and scope for further improvement. The study lasted for approximately 40 minutes and each expert user was given $20 compensation.

5.1.3 ***Results:*** From the survey results (Figure 6) and conversational interview, it was observed that experts agreed that the guided activities in VR would be sufficient to provide learning objectives and novices would benefit from using this simulator. A few direct quotes from the experts included: *"It gives a general idea and points in the correct direction and also, they [novices] would be able to repeat the activity."*, *"Augmented [Miller Arc] trainer does not provide information about wire change, VR is better in those aspects."* and *"I liked the sound and visual feedback [during the virtual welding]"*. According to the experts, the content progression was enough to perform the wire change on the real machine. Comments about the improvements in the system were noted, including: *"Switch the machine, cut the wire, two steps [were needed to be performed] back to back, [try to] pause [in between] and cut that into two different steps"*, *"keep more control of angles, speed [during virtual welding]"*.

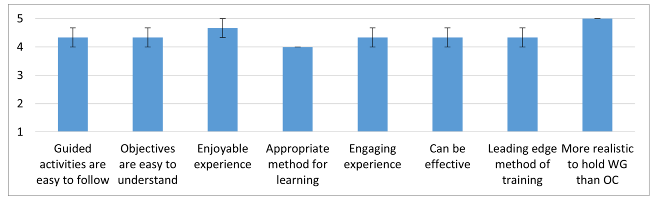


Figure 6: Expert Survey Results from Pilot Study (5-point Likert Scale rating where 1=Strongly Disagree, 2=Disagree, 3=Neutral, 4=Agree, 5=Strongly Agree)

This initial user study affirmed that the VR simulation met a reasonable expectation for ease of usability and engaged the learner in an adequate approximation of an on-the-job welding experience needed for further testing. After getting initial confirmation about the usability of the application, we were confident to perform the user study with the welding novices to evaluate the system performance after refining the system with a few more details as pointed out by the experts.

5.2 User Study and Evaluation:

5.2.1 ***Study Setup:*** The study was conducted with 24 participants (9 female, 15 male)(Age Range (number of users)=18-24 (9), 25-34 (11), 45-54 (1), 55-64 (2), 65+ (1)) without any prior welding experience who were recruited by word of mouth. Nine users had prior experience with VR while the remaining 15 were novices in VR. During this study, the usability of the system was measured while examining how users interacted with the training tool and what features they expected to achieve using the system. Each user study session was divided into two activities, the non-welding activity followed by the welding activity. The non-welding activity was performed to evaluate user-experience of the system and effectiveness of the virtual training to transfer skills to the real-world environment. In the welding activity, a comparative study was performed for testing the engaging capabilities of WG vs. OC.

5.2.2 ***Study Procedure:*** For the first activity, users were randomly assigned to undergo either VR (N = 12) or video-training (N = 12) in preparation of performing a wire change on a real welding machine. Pertaining to the relevance of video training in welding and industrial maintenance [68] combined together with the widespread availability of video materials [30], and the greater effectiveness of information transfer compared to text media [7][25] led us to select the video-training as the ideal counterpart against VR-training. Duration of the video used in the video-training was 2 minutes and was captured with the help of an expert welder. The use of the video material was validated upon the testing with the experts during the pilot study. The instructional video included a step-by-step tutorial on how to perform wire change as shown in Figure 7 and included both expert demonstration and narration. It is worth mentioning that the instructional video settings were attuned to utilizing both audio and visual channels and a run length of less than 3 minutes. These video parameters have been shown to make the instruction quality favorable for instruction transfer [57, 62]. The duration of the VR-training was approximately 10 minutes. The same instructional video was used for the interactive

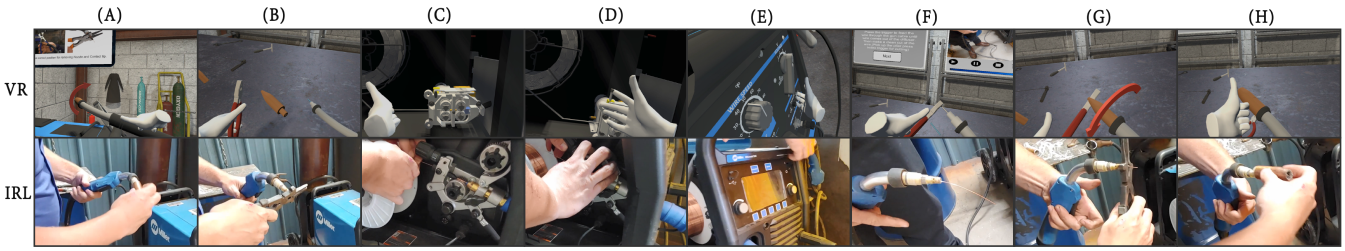


Figure 7: A breakdown of the activities during the Welding Wire Change Activity (from left to right) (A) Removing the nozzle and (B) contact-tip using pliers, (C) Releasing tension and feeding wire through drive-rolls, (D) closing tension, (E) turning the power switch on, (F) pressing trigger to feed the wire through welding gun, (G) Replacing the contact-tip and (H) nozzle on the welding gun

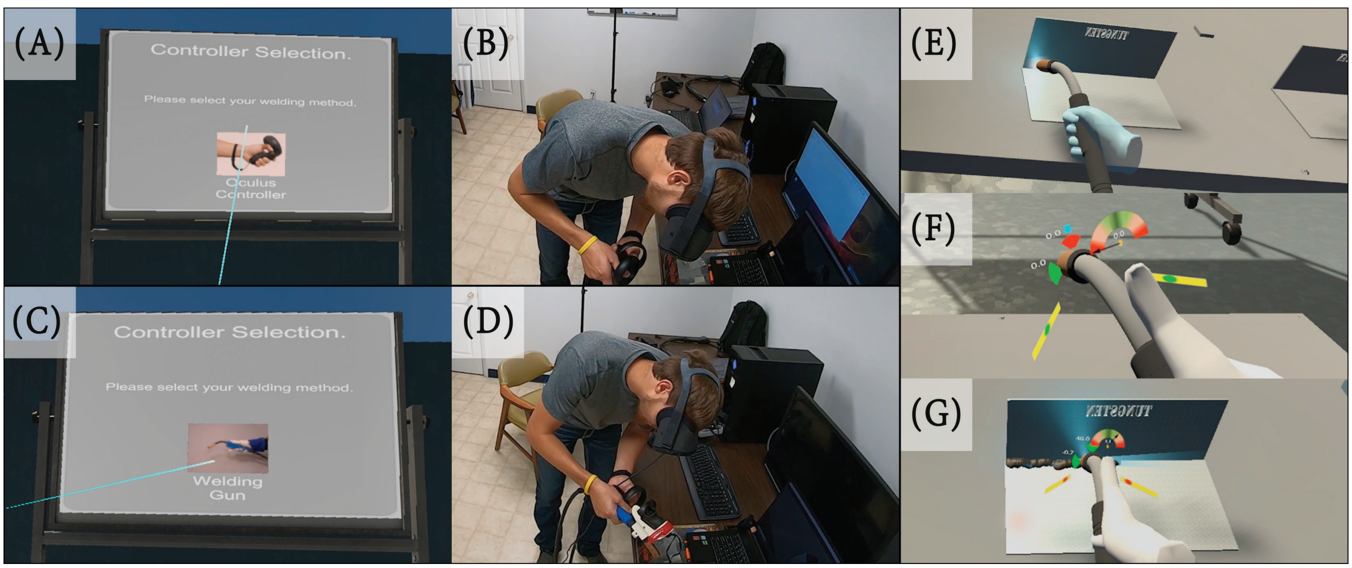


Figure 8: Description of the Welding Activity (A) User selects Oculus Controller and (B) Uses Oculus controller for virtual welding (C) User selects real welding gun and (D) Performs virtual welding using the real welding gun (E) Ghost demonstration before the trial run (F) Graphical feedback for welding parameters (G) Screenshot showing the user performing virtual welding

video tutorial in VR training. The PPE lesson along with the hands-on practice during the wire change lesson contributed towards the additional time requirements of the VR training. Moreover for the VR-training, a researcher explained the instructions verbally about the functions of physical buttons on the OC and virtual buttons in the system. After the training was completed, users were asked to perform the welding wire change activity on a real setup consisting of a Millermatic-215 welding machine connected to a WG and power supply. A researcher was present to correct errors after they were made, or to assist after it was requested and recorded. The breakdown of the steps in VR-training and the corresponding action shown during the activity in real life (IRL) is shown in Figure 7.

Following next was the welding activity which was divided into two sub-tasks, one involving the user performing virtual welding using the OC (Figure 8A,B) and the other using a real WG (Figure 8C,D). An avatar demonstration was shown to the users prior to performing the virtual welding to give them an idea of the correct hand pose associated with the process. This demonstration was pre-authored by a welding expert using the optimal values for the KPIs where the movement of WG along with the appropriate hand pose were recorded (Figure 8E). In regard to the real-time feedback, users had to perform the virtual welding while trying to maintain acceptable values for the KPI variables. Controller type order was counterbalanced such that 12 out of 24 users performed the activity using OC first and then real WG, and the other 12 users performed the activity in the opposite sequence. This counterbalancing was used to control and examine possible within-subject effects from the order of using the WG and the OC, and whether there are additional benefits (preference, learning, performance) of using the more realistic WG during VR. The study lasted for approximately 50 minutes and each user was given $20 compensation.

Data was collected for each user in terms of: (i) time required to finish each task, (ii) accuracy of the tasks, (iii) 5-point Likert

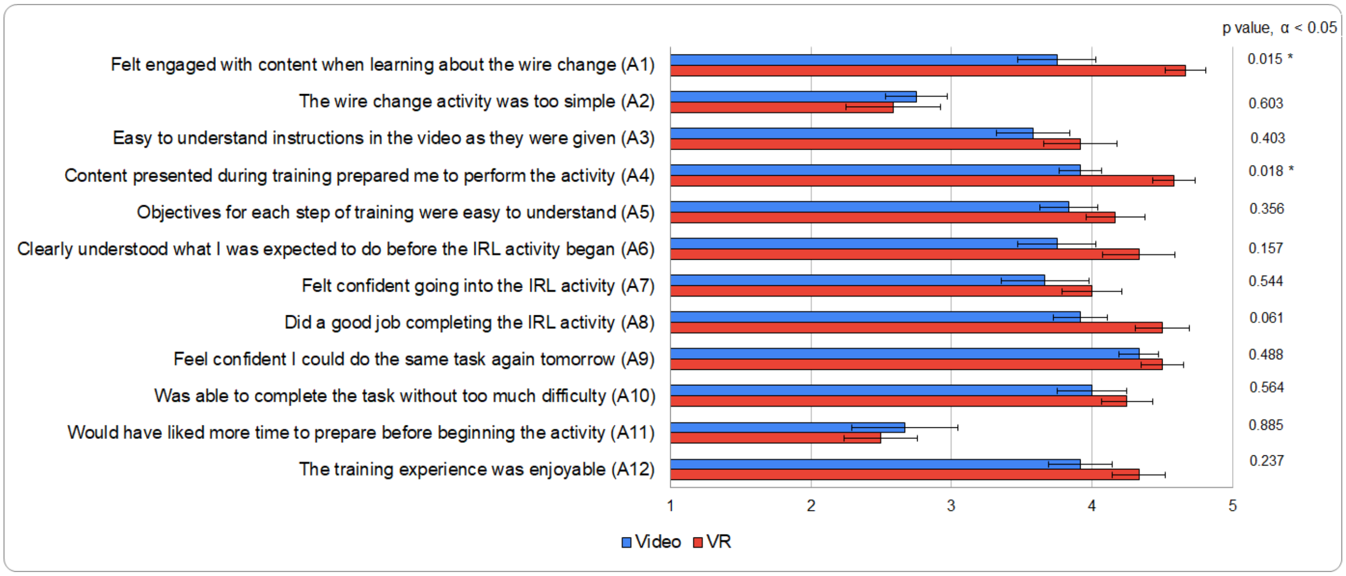


Figure 9: Average Participant Response to Post Weld Wire Change Activity Questionnaire showing the comparison between Video and VR-training (5-point Likert Scale rating where 1=Strongly Disagree, 2=Disagree, 3=Neutral, 4=Agree, 5=Strongly Agree)

scale-based questionnaire to test the usability of the system, (iv) 4-point variable score-based questionnaire to test for any motion sickness in VR, and (v) conversational interview. Each user study session was recorded from two camera views, first-person camera view in VR and third-person camera view in the real environment. The first-person camera view in VR was manually segmented to record the objective results in terms of time needed to perform tasks during the VR training. A researcher recorded the time and errors in real time during the welding wire change activity IRL. The third person camera record was manually checked later, in case review was needed or a mistake was missed. Data about the welding parameters was recorded from Unity for the welding activity. This data was analyzed later to obtain information about the time and accuracy to perform tasks. After each task, users recorded their experience with the system using a 5-point Likert survey. The design of the survey questionnaires was derived using the standard user-experience survey System Usability Scale (SUS) [10] and User Experience Questionnaire (UEQ) [50]. Details regarding the post activity questionnaires are provided as supplementary material for further reference. Immediately following the post welding activity questionnaire, the users were asked to fill a Virtual Reality Sickness Questionnaire (VRSQ) [43]. The VRSQ measures 9 symptoms of motion sickness in a VR environment under two main factors: a) Oculomotor (general discomfort, fatigue, eye strain, difficulty focusing), and b) Disorientation (headache, fullness of head, blurred vision, dizzy (eyes closed), vertigo). Users rated the presence of each symptom using a symptom variable score: 1=*None*, 2=*Mild*, 3=*Moderate* and 4=*Severe*. Next, the users were interviewed by asking about their experience with the system, comments on improvement, and potential of the system to be used for training. The subjective comments and suggestions from the users were audio-recorded and later used in the paper to explain the study results and inspire future design insights.

5.2.3 Results:

Activity 1: Welding wire change training using VR vs. Video. After all 24 users completed the first activity, the results from survey questionnaire and video analyses were analyzed to examine the usability of the virtual simulator with respect to the traditional video-based training. It was verified that the normal distribution assumption was not met by conducting Shapiro-Wilk normality test on the data (p<0.05). Therefore, Mann-Whitney U test was conducted on the survey results and the quantitative data for time of completion and errors made during the wire change IRL, to compare the performance of the two user groups. Average scores and standard error of the mean (SEM) values from the survey are shown in Figure 9 where A(i) indicate the relevant question after session 1. All Likert scale questions are reported with mean (M) and standard deviation (SD). The U-scores and p-values are later provided in the discussion section with statistical significance indicated by p<0.05.

From survey results (Figure 9), users were more engaged with the content presented in VR (A1, M=4.67, SD=0.14) as compared to video-training (A1, M=3.75, SD=0.28). VR-training instilled a higher level of confidence in users to perform the activity IRL (A7, M=4, SD=0.74) as compared to video-training (A7, M=3.67, SD=1.07). Users were more confident to perform the same task again if asked the following day (A9, M=4.5, SD=0.52) after VR-training than after video-training (A9, M=4.33, SD=0.49). Meanwhile, the video-training (A12, M=3.92, SD=0.79) received comparatively lowers scores than VR training (A12, M=4.33, SD=0.65) in terms of enjoyable experience. The objectives of the task were more clear after the VR-training (A6, M=4.33, SD=0.89) as compared to video-training (A6, M=3.75, SD=0.97). Users provided a lower rating when

Training Method	Average Time (Standard Deviation) (sec)	Number of Errors (Number of users who made the specific error)										
		Incorrect Gun Disassembly	Incorrect Plier Use	Incorrect Tension Use	Incorrect Wire Feed	Lose Control of wire	Incorrect sequence	Set wire incorrect length	Extra Steps	Lose Contact Tip/ Assembly	Wrong Power Button	Total
VR	251.58 (97.53)	4 (3)	9 (6)	2 (2)	5 (5)	5 (5)	6 (6)	6 (6)	1 (1)	3 (3)	1 (1)	42
Video	279.67 (106.45)	4 (3)	9 (8)	2 (2)	9 (7)	9 (9)	8 (6)	3 (3)	0 (0)	4 (4)	0 (0)	48

Table 4: Table showing Average Time Taken and Error breakdown for IRL Activity after VR/video-training

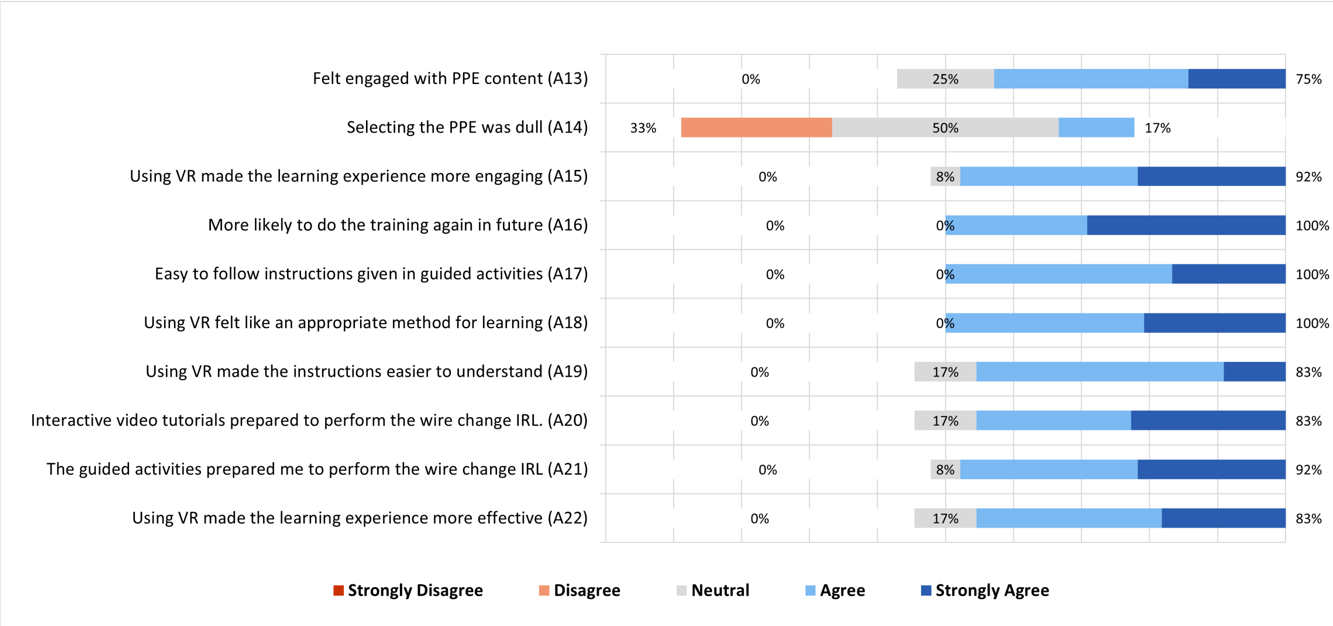


Figure 10: Post Weld Wire Change Activity Questionnaire Results for VR training with % of users from left to right who responded negatively (Strongly Disagree/Disagree), Neutral or positively (Agree/Strongly Agree)

asked if they were able to complete the tasks in real life without much difficulty for video-training (A10, M=4, SD=0.85) as compared to VR-training (A10, M=4.25, SD=0.62). Users who went through video-training (A11, M=2.67, SD=1.30) reported that they would have preferred more preparation time in contrast to VR-training (A11, M=2.5, SD=0.90). Users were more satisfied with their performance in real life after going through VR-training (A8, M=4.5, SD=0.67) as compared to video-training (A8, M=3.92, SD=0.67). Users also mentioned that the instructions were easier to understand in the VR-training (A3, M=3.92, SD=0.90) as compared to the video-training (A3, M=3.58, SD=0.90). Users reported that the objectives of each task were easier to understand in the VR-training (A5, M=4.17, SD=0.72) as compared to video-training (A5, M=3.83, SD=0.72).

Observations during the study and video recordings were also analyzed to obtain quantitative results in terms of time and accuracy to evaluate the system performance. These results are tabulated in detail in Table 4. The average time (in seconds) taken to perform the activity in real life after the VR-training was found to be M=251.58, SD=97.53, whereas for the video-training, the average time was comparatively longer M=279.67, SD=106.45. The sum of the total number of errors across all subjects, made while performing the activity in real life after video-training was 48, while for the VR-training was reduced to 42. An analysis of the different errors made during the activity is as follows. N1 and N2 are chosen to represent the total number of errors during the video and VR-training respectively.

Incorrect gun disassembly: During the initial steps, the nozzle and contact-tip needs to be disassembled from the welding gun. Few users tried to pull the nozzle instead of rotating it counter-clockwise for removing it. The same number of errors (N1=4, N2=4) were made in each case after video and VR-training. Some users misidentified the contact-tip on the welding gun or skipped the step of removing it after the nozzle was removed and were hinted to do so. ***Incorrect Plier Use:*** Some users incorrectly used the welding pliers (N1=9, N2=9) during the activity. A few times, the wrong grip of the plier was used to remove the contact tip or the nozzle from the welding gun. ***Incorrect Tension Use:*** Sometimes, the tension in the welding machine was either incorrectly set or released (N1=2, N2=2). Users tried to pull back the wire with the tension on, or forgot to set the tension before feeding the wire through the welding gun. ***Incorrect Wire Feed:*** This error was made when users tried to feed the wire through the drive rolls (N1=9, N2=5). Either the guides were missed, or the wire was fed all the way through the drive rolls by hand, or it was fed past the guide or the bent wire was not cut before feeding it through the guides. ***Lose Control of Wire:*** While feeding the welding wire through the drive rolls or during unwinding it from the spool, users lost

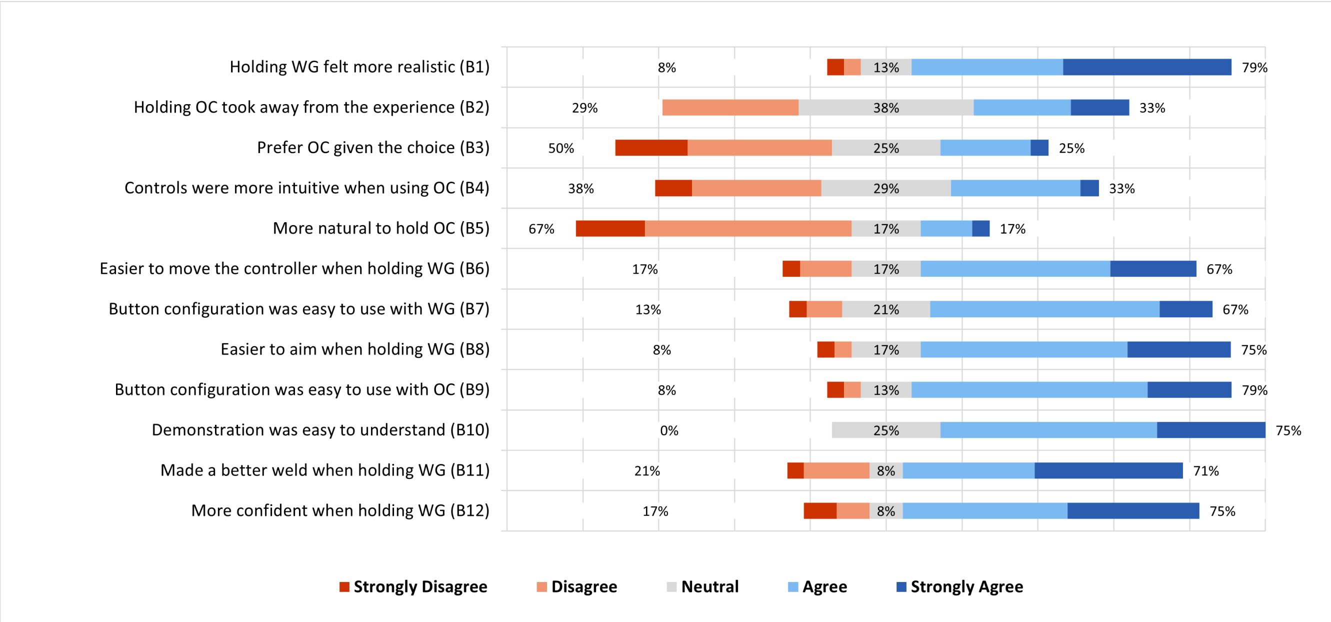


Figure 11: Post Welding Activity Questionnaire Results with % of users from left to right who responded negatively (Strongly Disagree/Disagree), Neutral or positively (Agree/Strongly Agree)

control of the wire (N1=9, N2=5). ***Incorrect Sequence:*** Few users had difficulty remembering the steps in order (N1=8, N2=6). For example, the contact tip was assembled before feeding the wire through the welding gun. The trigger was pressed before switching the power button. The nozzle was assembled before the contact tip, etc. ***Set wire incorrect length:*** Sometimes, users forgot to cut the wire or cut it short after feeding the wire through the welding gun (N1=3, N2=6). ***Extra steps:*** Users removed the wire incorrectly from the spool (N1=0, N2=1). ***Loose Contact tip/Assembly:*** The contact-tip was not tightened properly by using the pliers (N1=4, N2=3). ***Wrong Power Button:*** Some users had difficulty finding the power button to switch on the welding machine before feeding the wire (N1=0, N2=1).

The self-reported scores for the VR-training highlighting the overall training experience is also presented in Figure 10. Users reported that they felt engaged with the learning content when doing the PPE (A13, M=4, SD=0.74). Even though the PPE lesson was fairly easy to perform, they provided a low rating when asked if the PPE activity was dull (A14, M=2.83, SD=0.72). Overall, the users agreed that using VR provided them with an engaging learning experience (A15, M=4.33, SD=0.65). They were also eager to use it again in the future (A16, M=4.58, SD=0.51). Users reported that it was easy to follow instructions given in the interactive video tutorials (A20, M=4.25, SD=0.75) and the guided activities (A17, M=4.33, SD=0.49). Novices perceived the product as novel by providing a lower rating when asked if similar products exist in the market (A23, M=2.25, SD=0.87) and agreed about the potential of the system to be a leading edge method of training (A24, M=4.25, SD=0.75).

Activity 2: Virtual welding using OC vs. WG. The survey questionnaire following the welding activity was designed to perform a user-perception of the comparative analysis between the use of OC vs. WG. All Likert scale questions are reported with mean (M) and standard deviation (SD). From the results as shown in Figure 11, users reported that they felt to have made a better weld when holding WG (B11, M=4.08, SD=1.02). Higher scores for confidence while holding WG (B12, M=3.91, SD=1.10) indicate that the novices perceived the WG to be more effective to achieve the results. It was more realistic to hold WG than OC (B1, M=4.44, SD=0.75). Users provided a low rating when asked if they would prefer OC (B3, M=2.40, SD=1.10) and if it was more natural to hold OC than WG (B5, M=2.24, SD=0.99). It was easier to move the controller as desired when holding the real WG (B6, M=3.72, SD=0.92). Users were able to aim the virtual WG easier when holding WG (B8, M=4.08, SD=0.93). The demonstration was easy to understand prior to virtual welding (B10, M=3.76, SD=0.81) and the button configuration was easy to use (B9, M=3.72, SD=0.83). Moreover, there were some interesting observations based on VR experience of users in the welding activity. As expected, users with VR experience gave a slightly higher rating about the ease of button configuration (88.9%) and felt to have made a better weld (88.9%) as compared to the VR novices. This can be realized because of the extra effort in the part of VR novices to adapt to the new technology. It is also important to mention that despite the lack of experience, the ratings provided by VR novices for the above options (86.7 and 73.3%, respectively) were still high, which further justifies the accessibility of the system across users of all skill sets.

Virtual Reality Sickness Questionnaire. The results from VRSQ are shown in Table 5. The final mean score for VRSQ was calculated

VRSQ score options	Oculomotor				Disorientation				
	General Discomfort	Fatigue	Eyestrain	Difficulty Focusing	Headache	Fullness of Head	Blurred Vision	Dizzy (eyes closed)	Vertigo
None	21	20	21	18	23	22	18	23	21
Mild	3	3	1	5	0	1	6	1	3
Moderate	0	1	2	1	1	1	0	0	0
Severe	0	0	0	0	0	0	0	0	0

Table 5: Table showing number of users who reported 1=*None*, 2=*Mild*, 3=*Moderate* and 4=*Severe* for the symptoms in VRSQ

as 5.56 (out of 100), indicating that participants, on an average, experienced little or no motion sickness using the VR simulator. 15 users (62.5%) reported no effects for all symptoms on the VRSQ. 9 users reported *Mild* score for one or more symptoms from general discomfort, fatigue, difficulty focusing, nausea, blurred vision, dizzy eyes and vertigo. 3 users reported *Moderate* score for one or more symptoms from fatigue, headache, eye strain, difficulty focusing and nausea. None of the participants rated the symptoms under *Severe* in VRSQ.

To account for the minor motion sickness symptoms reported during the activities, future experiments can be conducted with varying interaction time periods and difficulty levels to allow for more comfortable and shorter learning sessions. Finally, advancements in the recent HMD devices including higher resolution, weight reduction, lower visual latencies and improved ergonomics may continue to minimize the motion sickness symptoms in VR experiences [84].

6 DISCUSSION AND FUTURE WORK

From the findings of the study and the qualitative feedback from the conversational interview, we try to answer the research questions that were posed before.

(1) To what extent does the use of interactive video tutorials and guided activities inside VR enhance the student's performance and user experiences as compared to 2D video-based training alternatives? The findings from the study reveal that VRWeldLearner enhanced students' performance and user experiences as compared to 2D video-based training methods. Users reported higher scores for engagement (A1 [U=30, p^*=0.015], A12 [U=51.5, p=0.237]), confidence (A7 [U=61.5, p=0.544], A9 [U=60, p=0.488]), performance satisfaction (A8 [U=39.5, p=0.061], A10 [U=62, p=0.564]), understanding of tasks (A3 [U=57.5, p=0.403], A5 [U=56, p=0.356], A11 [U=69.5, p=0.885]), interest in learning (A2 [U=63, p=0.603]) and clarity of concepts (A4 [U=31, p^*=0.018], A6 [U=47.5, p=0.157]) in VR-training as compared to video-training. It can be argued that the learning-by-doing affordance provided by the VR training platform helped in understanding of maintenance operations involved during welding wire change while engaging the learners with hands-on experience similar to the actual trials. In contrast, the 2D interface-based materials lacked to provide the necessary hands-on experience required to understand and develop the skills. Users commented *"The content (in VR) provided enough information to understand what I was doing"*, *"That part [welding wire change lesson] is good, because after the training in VR, I think I have fully understood the process. In reality, I had never seen the machine before, but I could perform the key steps."*.

Even though VR-training took comparatively longer time than video-training, it was observed that the task completion time was almost 10% faster [U=56, p=0.356] and accuracy was 12.5% higher [U=63, p=0.603] for users who were trained using VR which further affirms the advantages of VR over 2D video-based methods. From the error breakdown analysis, there were some interesting observations. The VR-training helped in remembering the sequential steps better than the video-training. This can be realized owing to the experiential nature of VR-training that has been proved useful for skill retention in users [1]. VR-training also provided a greater sense of the spatial location and function of objects. This can be sensed from the lesser number of errors made by the users in misidentifying the contact-tip and feeding the wire incorrectly through the drive rolls in VR-training as compared to video-training. Next, the impact of the VR training on knowledge acquisition, and skill development and transfer in users is discussed in detail.

Perceptual skills: Training in VR helps in the development of spatial awareness and relationships by enabling the user to interpret and use the surrounding virtual space in an organized way through execution of spatial commands e.g., cutting the tip of the wire or inserting the wire through the drive rolls. It helps in developing the visual spatial skills to understand directional language concepts in relation to the body and with respect to the work context which allows the user to apply these concepts to the external world. The experiential learning also promotes the understanding of the user's virtual body parts (e.g., hands of the first-person virtual self) and external objects in relation to each other or other objects while keeping the body as the reference point for identifying the position of objects in space. An example of this can be shown when using the specialized welding pliers. The user must identify the correct part of the pliers, how it relates to the welding gun (contact tip, nozzle, or wire), and how to manipulate it to get the desired results (rotating to remove contact tip or nozzle, pinching to cut wire, etc.)

Cognitive Skills: The hands-on experience in VR adds extra privilege in clarifying or rectifying concepts stored in user's working memory gained during the interactive video tutorial. It is often the case that the lack of prior hands-on usually leads to following a trial-and-error approach to get moderately complicated tasks correct when the visual system cannot supply the missing information from the memory [3, 33]. The experiential learning affordance provided by VR, however, helps to stabilize this information during the learning process, and later, enables the user to perceive and identify the process and object when only a part of it is visible. E.g., during feeding the wire through the drive rolls, users trained using VR were more confident and committed less errors. This can be reasoned from the fact that their visual system could supply the missing information learnt from during the experiential learning process. Moreover, the comparison of the average time taken to complete the activity in VR and video-based training indicates in favor of faster processing speed and recall of information during performance of tasks for users trained using VR. A user who was trained using VR commented, *"I could remember everything [in the wire change activity] and do it in person, overall I could remember the sequence of doing things"*. The study analysis shows that the VR training ultimately leads to: (i) better retention and recall of the information when needed to apply in real world, (ii) less omissions of tasks, (iii) improvement of sequential memory, thereby enabling the user to retain, remember and recall a sequence or pattern in a specific order, and thus (iv) improving the overall comprehension of the task and user's confidence to perform the task.

Motor Skills: Finally, it can be realized that VR also provides a platform to enable the users to manipulate objects and develop the necessary motor skills e.g., *discrete* in case of switching the power button on the welding machine, or *continuous* as in pressing the trigger on the welding gun to release the wire, or *fine* as in inserting the wire through the drive rolls precisely, or *gross* as in opening the cover of the welding machine. The training also helps in the development of bilateral motor coordination intended to improve the ability to synchronize and use either hand for different functions e.g., in the case of using welding pliers to remove the contact tip on the welding gun where the user needs to move both hands in a smooth coordinated manner. Having been already experienced these activities in VR helps the user organize and plan activities and make automatic adjustments when required to perform similar tasks in the real world.

The number of errors *Set wire incorrect length* was higher in case of VR-training as compared to video-training. During the VR-training (*Step 11*, Figure 7F), the highlighted wire-tip provided a wrong impression about the length of welding wire to be released by pressing the trigger on the welding gun. This can be solved by highlighting the tip of the wire after releasing it a few inches. The error involved with *Incorrect Plier Use* was also high during the activity. An extra step could be added where the user is asked to identify the different parts of the specialized welding pliers (large/small serrated holes and cutter) before using the tool. This step can improve the user understanding related to the correct usage of pliers during the wire change. Also, there was an extra error made by a user trained using VR while removing the wire from the spool. This particular step was not covered as a part of the training process. However, the above changes are minor fixes that are planned to be added in the revised version of the learning module.

(2) To what extent is there an improvement in performance in using the welding gun instead of the Oculus Controllers during virtual welding? Data values were collected from participants during the welding activity. Participants were split and performed the welding activities with the welding gun or the Oculus controllers. Accordingly, the users' performances were examined on the following parameters: (a) distance, (b) travel angle, (c) work angle, (d) speed, and (e) combined KPIs. For participants using the welding gun, it was found that the average run-time accuracy within the acceptable ranges for the previous parameters was: (a) 42.86%, (b) 95.24%, (c) 66.67%, (d) 66.67%, and (e) 23.81%, respectively. Likewise, for participants using the Oculus controllers, it was found that the accuracy within the acceptable ranges for the previous parameters was: (a) 37.50%, (b) 66.67%, (c) 45.83%, (d) 37.50%, and (e) 12.50%, respectively. The results are displayed in Table 6.

Thus, it can be observed that participants' overall performance and accuracy were improved with the use of the welding gun (and mount) when compared to the use of the Oculus controllers alone. This can be argued by saying it was easier to position the virtual WG using the real WG than the OC owing to the sense of realistic haptic experience provided by the former. As one of the users remarked, *"Pointing with the angles, it [was] easier to do it with the WG. With the OC, even if the values were correct, it did not feel right."*. High ratings about the realistic experience and intuitiveness of the WG as compared to the OC made the former a better choice for virtual welding for the users. During virtual sessions, users experienced the feeling of moving a welding torch owing to the tactile sense of touch provided by the real welding gun. The skin indentation feedback provided by the welding gun on the user's dominant hand enabled tactile sensations primarily linked to grasping and manipulation. The realism obtained in VR by adopting the real instrument and its attributes such as mass and shape altered their perception and physiological arousal inside the virtual environment [47]. Users described their experience during the interview session *"[I] really like WG version, [I] can feel the weight, [it is] more intuitive, the important part is how I feel about holding the WG"*, *"The WG was more comfortable to use, you can feel it and it is easier to hold and find the right position"*. This further suggests that there is a need to design VR devices specific to the context and modeled after the tools used in workforce context rather than a one-size-fits-all VR hardware (like the Oculus) for better uptake.

Condition	Average Time (Standard Deviation) (sec)	Distance	Travel Angle	Work Angle	Speed	Combined
WG	115.25 (62.48)	42.86	95.24	66.67	66.67	23.81
OC	103.44 (60.08)	37.50	75	50	50	12.50

Table 6: Users' performance in average time to complete activity and percentages when the KPIs fall within acceptable ranges. The column *Combined* shows the values when all KPIs are met.

By replacing the OC from users' hands with a real WG, a more realistic experience was provided at an affordable price as compared to other virtual simulators. Our hypothesis that the proposed solution for visuo-haptic guidance towards enhancing immersion inside the virtual environment was further strengthened by the positive comments that were received from the users. Users pointed out *"Virtual welding experience was great, especially the indicators helps to learn how to use WG"*, and *"I like [the] idea of holding WG rather than OC. That way I will have the memory when I actually do it [welding] where I know how to hold it [WG] than how to hold the controller"*. This can be reasoned by stating that interpreting visual information from the graphical feedback accompanied by the touch, feel and force provided through the haptic perception from the real welding gun helped to develop the internal awareness of the hand postures and movements associated with correct welding procedures. Virtual cues provided through the KPI indicators could teach correct positioning and use of user's hands in relation to the associated objects. Using the system, novice welders can practice welding at remote locations with the help of a standalone OculusQuest^{TM} and a WG.

Visuo-haptic guidance and the development of psychomotor skills: Psychomotor skills are a link between various cognitive and physical processes that necessitate bodily motions and mental stimulation to achieve their goals [49, 90]. To execute diverse jobs, welders employ psychomotor skills to manipulate and retain control over a molten weld puddle mostly through applying the four fundamental welding operation abilities or the KPIs, keeping the right arc length, maintaining the proper travel angle and work angle, and maintaining the proper traverse speed [9, 11]. These psychomotor skills are related to hand-eye coordination, hand and arm movements, and body positioning [94]. During the early phases of training when the student may lack the requisite psychomotor skills, physical guidance is provided by the instructor in form of direct assistance to prevent the learner from making mistakes in the task, which is effective for development of skills. The simulating approach in VR is designed to mimic the physical guidance in real-world training to display the proper force/position/orientation relation for achieving hand-mind-eye coordination skills. With practice, learners can internalize the knowledge of welding related specifications, so responses become automatic and instantaneous. After checking that the system provides acceptable results in the short term, we are planning to conduct a study to check whether long-term exposure of the virtual simulator would lead to the psychomotor skill development for welding.

From the interview, it was observed that some users felt a little disconnected with having to press the trigger button on the left hand controller to initiate the virtual welding while using the real WG, *"The button on the left hand seems to be [a] practical solution, but it would be better to somehow connect the button on the WG to the application"*. To address these issues, we plan to improve the existing 3D-mount such that pressing the trigger button on the WG could actually trigger the virtual welding. It would be interesting to extend the haptic perception from the WG to include forces and/or vibro-tactile sensations [73] and develop experiments to compare with the current results. There is an additional challenge of replacing the correct device from the user's hands based on learning requirements. During the user study, when switching from using the OC to the WG, the OC was mounted to the WG by a researcher. The impact on the user from the switch was minimal, and therefore, no feedback was collected regarding it's impact on the user's perception. However, considering the modular structure of the learning units and easy fit of the device, we assume that the impact of the device replacement on the user perception would be low, and plan to verify this as a scope of future work.

Thus, it was found that users can use VRWeldLearner to learn about the fundamentals of MIG welding and successfully perform the machine operations in the real world after getting trained with the system. The survey results provide strong evidence that our system is accessible, engaging, and effective in transferring skills into the real-world. We demonstrated that the design guidelines of VRWeldLearner can provide sufficient information to novices to familiarize, learn and repeat welding concepts in an intuitive and immersive environment. While the prototype that was tested on the users is not exhaustive in that it does not contain the modules end-to-end, it tests on the added modules that commercial VR simulators do not provide. We plan to build on the existing prototype in future to include the remaining exercises associated with the learning modules. In the light of the design guidelines used in VRWeldlearner, the authors have featured aspects of the system that are geared towards promoting easy accessibility of welding instruction and self guided learning for welding novices in general. This design has been planned in such a manner that specific content may be presented within a modular and flexible framework. A comprehensive analysis is however recommended as an alternative direction for future research in evaluation of design features in similar contexts.

7 CONCLUSION

We have presented VRWeldLearner, the system design of a VR-based MIG-welding training simulator, modeled based on our reasoning that a high-fidelity, holistic, low cost Virtual Reality training system could be more easily adapted and distributed to increase training availability. We have actively consulted with welding training experts and gathered their feedback to develop the learning objectives by following the backward design model from the approach of learning sciences. We structured the learning modules of VRWeldLearner by following a set of deign guidelines. The user study on 24 welding novices demonstrated how the learning modules in our system can help novices learn welding concepts in a guided format. The study results confirmed the usability of the system. First, we found that the system features are easy to use, and are effective in transferring skills to the real-world environment. Second, our proposed alternative for visuo-haptic guidance obtained by replacing Oculus controllers from users' hands with a real welding gun provided a more realistic learning experience for novice welders to practice skills during virtual welding while improving performance. Participants of the user study commented in affirmation about the ability of the system to provide training experiences for welding novices. We envision that by using the system, the lead and training time associated with the traditional welding training programs can be reduced, resulting in a faster certification process. The application can also be deployed in non-welding environments such as libraries, K-12 schools, community colleges, and correctional institutions to promote interest and welding education for choosing the trade as a career choice. Additionally, the concepts developed and proven effective for welding can be adapted and applied across other industries to develop VR applications for training complex processes.

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