Virtual Reality in Welding Training and Education: A Literature Review

Abstract

The welding workforce is facing a deficit of skilled welders, highlighting the need to develop more efficient and effective welding training methods. Virtual reality (VR) technologies have been adopted to create VR welding simulations for educational and training purposes. The purpose of this literature review was to collect and analyze peer-reviewed research, published between 2012-2022, regarding VR technology applications in welding training. The concept of Engagement in Blended Learning Environments served as our research framework. In the context of welding, VR welding training is a relatively new approach that functions as a blended learning environment. During data collection, we identified 31 articles; however, following analysis and coding, 13 were excluded, for a final N=18. Through a process of triangulation, we identified themes across existing research to highlight trends, recommendations for real-world welding practice, and recommendations for future research. Four main research themes emerged from the literature: 1. Comparison of Approaches, 2. VR as a Teaching Tool, 3. System Development, and 4. System Testing. Six future research recommendations were identified and grouped, including the recommendation to compare virtual weld performances to live weld performances. Four practitioner-based recommendation themes were identified, including the recommendation for instructors to develop their own knowledge and skills related to VR welding technology. From this review, we identified gaps in the existing literature and made recommendations for future research on VR welding training.

Keywords: virtual reality, virtual welding, welding education, welding training, blended learning

Introduction

Welding is a critical sector of the global manufacturing and fabrication industries, including the automotive, construction, pipeline, and energy industries (American Welding Society, 2022). The welding workforce is currently facing a deficit of skilled workers, highlighting the need for more effective and efficient welding training (American Welding Society, 2022). Various technological advances have been developed for welding training, including virtual reality (VR) welding training simulations (Liang et al., 2014). This literature review explores existing research investigating the use of VR technology in welding training and educational settings.

Industry Challenges

As of 2020, 44% of the U.S. welding workforce was 45 years and older (Buel, 2021). Accordingly, it is expected that much of the welding workforce will soon retire, resulting in a projected workforce deficit of approximately 366,000 skilled welders by 2024 (American Welding Society, 2022). As countless economies and industries rely on welders to manufacture and fabricate products, welding industry leaders (e.g., Career and Technical Education [CTE] program directors, School-Based Agricultural Education [SBAE] instructors, and welding instructors) will need to train highly proficient welders at an expedited rate to address the projected workforce deficit (American Welding Society, 2022)

In training highly proficient workers quickly, an obstacle that welding industry leaders and trainers will need to overcome is the inherently difficult nature of traditional welding training which first provides welding knowledge through lessons, typically in classroom settings, then introduces hands-on learning (Lincoln Electric, 2022). In the initial lessons, trainees learn about welding machines and equipment, proper personal protective equipment (PPE), safety protocols, welding processes and respective consumables, metallurgy concepts, welding techniques, and welding parameters (Lincoln Electric, 2022; Whitney &

Stephens, 2014). Once trainees are familiarized with these concepts, they begin hands-on learning by performing 'practice welds', traditionally in workshop settings. In traditional welding workshops, trainees are placed into isolated weld booths for safety (Lincoln Electric, 2022) then asked to perform certain weld processes and specific configurations. Trainees present their completed welds to instructors who then predict what the imperfections are and where they originated from (Lincoln Electric, 2022). Instructors then suggest techniques and tips for the trainee to improve their weld performance. This cycle of repetitive weld practice continues until the trainee can consistently produce high-quality welds (Ilyashenko et al., 2019).

Traditional welding training has many challenges, particularly those related to economic, complexity, and intensive mentorship issues (White et al., 2010). Economic drawbacks are related to costly training. Welding training requires a mass amount of consumable material and energy in the form of metal (e.g., steel, aluminum, titanium, cast iron, copper, brass), natural gas (e.g., argon, helium, hydrogen, oxygen, carbon dioxide, nitrogen), welding wire (e.g., manganese, silicon, titanium, aluminum, copper), consumable and non-consumable electrode rods (e.g., mild-steel, cast iron, stainless steel, high-tensile steel, copper, bronze, brass) and electrical power consumption (Adams et al., 2022). Along with the reliance on expensive materials and consumables, welding machines also require frequent maintenance and care which requires time, manpower, and, in many cases, monetary inputs ranging from $40 to $200+ (Miller Electric Mfg. LLC, 2005).

The complexity of welding also presents challenges in traditional welding training. Welding is a difficult and precise skill; training requires extended periods of practice to master the concepts, performance, and troubleshooting that competent welders require (Lincoln Electric, 2022). Traditional welding training also demands a high level of independent, self-assessment of individual welding performance (Whitney & Stephens, 2014). Because of this, traditional welding training may not be the most effective learning method for everyone, as some learners require alternative methods for understanding complex concepts, such as those that characterize welding (Kulkarni et al., 2022).

Traditional welding training also requires considerable mentorship and instructor intervention for trainees who do not excel at self-assessment and troubleshooting (Lincoln Electric, 2022). Faced with the surge of retiring welding professionals, the number of qualified welding instructors will likely not be sufficient to train and provide adequate mentorship to the number of highly skilled welders the industry demands (Ipsita et al., 2022).

Virtual Reality Welding Simulations

In response to the pressing need to develop a large and highly trained workforce and to address the challenges associated with traditional welding training, there has been research investigating the incorporation of various VR technology training applications into welding training programs and educational courses (Dalto et al., 2010; Stone et al., 2013; Wells & Miller, 2020a; Wells & Miller, 2020b). VR technologies create fully immersive artificial or computer-generated virtual environments (Ves) equipped with visual, audial, tactile, and other modalities (Benson et al., 2016). VR simulations are typically implemented using oculus goggles, head-mounted displays (HMDs), sensor-filled gloves, and/or haptic input attachments. These devices aid the system in providing a complete VE where users can perform tasks. VR technology has most commonly been adapted as a tool for medical, military, aviation, automotive, and space training purposes; however, more recently, VR technology has also been adapted for the welding industry (Hasan et al., 2017).

Virtual cues are one feature of VR welding technologies that can aid welders in understanding complex concepts of welding (Stone et al., 2013). Virtual cues display the welding parameters that determine a high-quality weld. Another feature of VR welding technologies is the instant weld quality grading (Lincoln Electric, 2022). The instant, personalized feedback allows for faster training procedures than that of traditional welding training, while still providing meaningful learning (Stone et al., 2013).

Conceptual Framework

The Engagement in Blended Learning Environments conceptual framework was used to guide our study (Halverson & Graham, 2019). This conceptual framework explains that educational outcomes, academic achievement, and satisfaction are directly correlated to the learners' level of engagement in their blended learning environments. Blended learning environments utilize increased flexibility and personalization, opportunities for interaction, and technical advantages (e.g., online learning, simulations, gamification) to maximize engagement (Halverson & Graham, 2019). A learners' engagement level depends on the cognitive and emotional energy they dedicate to their lesson or activity. The more cognitive and emotional energy dedicated, the more likely the learner is to achieve academic success and satisfaction.

In the context of welding, VR welding training is a relatively new training approach that functions as a blended learning environment. Learners are provided a unique learning environment in the VE and are given personalized feedback regarding their welds from the VR welding simulation. Interactivity allowed by the VR welding simulation requires more understanding and involvement from both the learners and their peers during the welding training. This study sought to identify the research topics within the existing literature regarding VR welding technology as aligned with the Blended Learning Environment.

Purpose and Objectives

The purpose of this literature review was to collect and analyze peer-reviewed, published research regarding VR technology applications in welding training and education. In this review, we identified themes across existing research to highlight trends, recommendations for practitioner-based welding using VR technology, and recommendations for future research. The objectives of this literature review were to:

1. Determine the number of existing research articles published between 2012-2022 regarding VR technology implementation in welding training and education.
2. Determine which research topics are prevalent within the existing literature regarding VR technology implementation in welding training and education.
3. Identify and interpret the key themes prevalent within the existing literature regarding VR technology implementation in welding training and education, and outline recommendations for practice and future research.

Methods

This literature review gathered, quantified, and interpreted existing research focused on VR technologies in welding training and educational environments. The design was partially adapted from Kovar and Ball (2013) and three strategies were used: 1) definitive search strategies, 2) inclusion criteria, and 3) source analysis and categorization.

Search Strategies

To collect articles for this review, we searched various electronic databases, including Google Scholar, Scopus, IEEE Xplore, Education Resources Information Center, Web of Science, and ResearchGate. We also searched academic journals related to VR and welding including Journal of Agricultural Education, Career and Technical Education Journal, International Journal of Mechanical Engineering, Technology Journal, Welding Journal, and Virtual Reality Journal. Combinations of the keywords "virtual reality", "welding", "welding training", "welding education", and "VR applications" were used to identify articles. The article search began 12 July 2022 and concluded 2 September 2022. A follow-up search was conducted on 16 December to ensure no new literature had been published in 2022.

Inclusion Criteria

Inclusion criteria for our search encompassed specific populations, interventions, publishing dates, and publishing formats (Table 1). Populations were welding trainees, welding and non-welding students, experienced welders, and welding and non-welding trainers/instructors, without age or experience limitations. Interventions were VR technologies and applications incorporated into welding training and educational environments. Literature was peer-reviewed and published as a manuscript in a refereed journal between 2012 and 2022; conference proceedings, theses/dissertations, and patents were excluded.

Table 1

Inclusion and Exclusion Criteria for Literature Collection

Inclusion criteria	Exclusion criteria
English language publication	Non-English language publication
Publication regarding a welding training/education environment	Publication not involving a welding training/education environment
Publication with listed references/sources	Publication without references/sources
Publication investigating immersive virtual reality technology	Publications using augmented reality or robotic welding technology
Publications and reports in peer-reviewed journals	Conference proceedings, theses/dissertations, patents

Analysis and Categorization

Article analysis and categorization involved an initial screening stage followed by a coding stage. For screening, article title and abstracts were cross-referenced with established inclusion/exclusion criteria. If the titles and abstracts did not contain adequate information for screening, the introduction, methods, discussion, and conclusion were combed for further consideration. Our data collection resulted in a total of 31 articles related to the investigation of VR technology implementation in welding training and/or educational settings. Following the literature analysis and coding stages, 13 articles were excluded. Articles with significant grammatical errors, misconstrued data, and/or misrepresented data were excluded from further analyses. Other article exclusions included robotic welding technology research focuses, conference proceedings publications, predatory journal publications, and plagiarism. All articles collected for this study were cross-referenced using Opensource software to determine if the articles were published in predatory journals. Once final article exclusions were made, 18 articles remained.

The coding stage involved full-text evaluations where we (i.e., the three authors) independently identified key findings, themes, research methods, and recommendations of the collected articles (*N*=18). As recommended by Kovar and Ball (2013), we conducted peer debriefings to externally review our findings. We discussed our independent coding/theming of the articles and justified our reasoning. Following the peer debriefings, we then decided which suggested code/theme best represented each article, as well as which research and practice recommendations were presented by each article. This method of data triangulation corroborates findings and increases the reliability of our results (Kovar & Ball, 2013). Sub-themes were identified within themes that comprised topics important to the focus of our research. Sub-themes exist under the umbrella of themes, sharing the central organizing concept as the theme, but highlighting a specific element of the research topic. We used sub-themes to better interpret the results of this literature review. Emerging themes, though rarely used, describe themes that emerge from few sources, but that highlight important or novel research ideas, topics, or discussions. In this review we identified two emerging themes, presenting significant contributions to the research topic, from the collected literature.

Results and Discussion

Research Topic Themes

From analyzing and coding the collected articles (*N*=18), four research topic themes were identified: *1. Comparison of Approaches, 2. VR as a Teaching Tool, 3. System Development, and 4. System Testing* (Table 2). In the case of one theme, *2. VR as a Teaching Tool,* three sub-themes emerged: *2.1 Performance Outcomes, 2.2 User Perceptions, and 2.3 User Experiences.* Some articles were coded for multiple themes; accordingly, the number of articles examined is less than the number of themes coded for. For example, an article could code for both *1. Comparison of Approaches* and *3. System Development*.

Table 2

*Identified Research Topic Themes and Sub-themes for Virtual Reality (VR) Welding Literature Analysis, Theme and Sub-theme Descriptions, and Number of Articles Categorized into Themes (*N*=18)*

Theme	Description	Articles (*n*)
1. Comparison of Approaches	Research comparing implementation of VR welding training methods to other forms of welding training	4
2. VR as a Teaching Tool	Research investigating the teaching aspects and outcomes of VR technology implementation in welding training	14
2.1 Performance Outcomes	Research that specifically evaluates performance outcomes from VR technology implementation in welding training	8
2.2 User Perceptions	Research that investigates user perceptions of VR technology (e.g., acceptance, dislike)	8
2.3 User Experiences	Research that investigates user experiences of VR technology (e.g., frustration, comfort)	4
3. System Development	Research that presents and discusses VR welding training system development	6
4. System Testing	Research that tests various aspects of VR welding training system(s)	5

Comparison of Approaches

The first theme, identified in four articles, was *1. Comparison of Approaches*. Articles with this theme compared and contrasted different aspects and outcomes between welding training methods. Within this theme, three articles compared full VR training to traditional live welding training (Liang et al., 2014;

Shankhwar & Smith, 2022; Shankhwar et al., 2022). By comparing traditional welding training to VR training methods, advantages were identified, such as material savings (Liang et al., 2014; Shankhwar & Smith, 2022; Shankhwar et al., 2022), increased learner satisfaction (Shankhwar & Smith, 2022; Shankhwar et al., 2022), and training time savings (Liang et al., 2014). Another key finding in these three articles was that trainees who underwent VR training experienced less mental and temporal demands, as well as less frustration, than those who underwent traditional training (Liang et al., 2014; Shankhwar & Smith, 2022; Shankhwar et al., 2022). The final article identified within this theme investigated a full VR welding training method against a VR integrated (partially VR, partially live; VRI) training method (Byrd et al., 2018). This study used simple weld configurations (i.e., 2F, 1G, 3F, 3G) and the Gas Metal Arc Welding process to evaluate welders' live and virtual abilities. It was demonstrated that welding training can successfully be presented in the VE; however, it cannot replace the actual act of welding from their comparisons to live welding training groups (Byrd et al., 2018). Therefore, live welding training will always be required. Understanding the effects of blended learning, such as VRI training, is critical to optimize welding training, as research demonstrates that virtual training requires acclimation time to both virtual and live environments (Byrd et al., 2018).

VR as a Teaching Tool

The second theme, identified in 14 of the 18 articles, was *2. VR as a Teaching Tool*. This theme encompasses research that investigated the teaching aspects of VR technology implementation in a welding training or educational setting. Due to the high volume and diversity of articles, this theme included three sub-themes: *2.1 Performance Outcomes, 2.2 User Perceptions,* and *2.3 User Experiences*.

Sub-theme *2.1 Performance Outcomes*, emerged from eight articles that evaluated the user performance outcomes of VR welding training methods (Byrd et al., 2015; Byrd et al., 2018; Huang et al., 2020; Liang et al., 2014; Shankhwar & Smith, 2022; Shankhwar et al., 2022; Stone et al., 2013; Wells & Miller, 2020b). Performance outcomes included weld quality scores, welding certification rates, welding parameter scores, dexterous abilities, and pre- and post-knowledge tests. Within this sub-theme, six of the articles examined various performance outcomes for beginning welders using the VR technology (Byrd et al., 2018; Huang et al., 2020; Shankhwar & Smith, 2022; Shankhwar et al., 2022; Stone et al., 2013; Wells & Miller, 2020b). The other two articles examined outcomes for experienced welders (Byrd et al., 2015; Liang et al., 2014). Five articles reported an increase in welding parameter scores and certification rates following pre- and post-examinations from VR welding training (Byrd et al., 2018; Huang et al., 2020; Liang et al., 2014; Stone et al., 2013; Wells & Miller, 2020b). Further, pre- and post-VR welding training knowledge tests indicated that participants gained more welding knowledge from the training (Shankhwar & Smith, 2022; Shankhwar et al., 2022).

Sub-theme *2.2 User Perceptions*, emerged from eight articles that examined the perceptions of students, teachers, and beginning and expert welders from integrating VR technology into welding training and education (Chung et al., 2020; Huang et al., 2020; Karstensen & Lier, 2020; Rodriguez-Martin & Rodriguez-Gonzalvez, 2019; Shankhwar & Smith, 2022; Shankhwar et al., 2022; Wells & Miller, 2020a; Wells & Miller, 2022). Six of the articles within this sub-theme collected the perceptions of beginning welders after using VR technology for welding training (Chung et al., 2020; Huang et al., 2020; Rodriguez-Martin & Rodriguez-Gonzalvez, 2019; Shankhwar & Smith, 2022; Shankhwar et al., 2022; Wells & Miller, 2022); these articles examined beginning welders' attitudes and acceptance of VR welding training, usability of VR technology, and motivation for using VR technology in welding training. The final two articles within this sub-theme collected perceptions of welding and SBAE teachers (Karstensen & Lier, 2020; Wells & Miller, 2020a). Karstensen and Lier (2020) reported that SBAE teachers found value in using VR technology for welding training. Wells and Miller (2020a) reported that, although SBAE teachers felt a degree of uncertainty, they also felt VR would positively impact their welding training programs.

Sub-theme 2.3 User Experiences emerged from four articles that evaluated the various experiences of students, teachers, and expert welders after VR welding training (Chung et al., 2020; Feier & Banciu, 2021; Karstensen & Lier, 2020; Rodriguez-Martin & Rodriguez-Gonzalvez, 2019). User experiences were evaluated using questionnaires (Chung et al., 2020; Rodriguez-Martin & Rodriguez-Gonzalvez, 2019), one-on-one and group interviews (Chung et al., 2020; Feier & Banciu, 2021; Karstensen & Lier, 2020; Rodriguez-Martin & Rodriguez-Gonzalvez, 2019), focus groups (Chung et al., 2020), and journal entries (Karstensen & Lier, 2020). Three articles examined the experiences of beginning welders (Chung et al., 2020; Feier & Banciu, 2021; Rodriguez-Martin & Rodriguez-Gonzalvez, 2019). Beginning welders undergoing VR welding training reported positive learning and usability experiences, high levels of learning satisfaction, and high levels of motivation to engage in the activity (Chung et al., 2020; Rodriguez-Martin & Rodriguez-Gonzalvez, 2019). Further, beginning welders experienced an increased level of importance for weld quality than they did prior to training with VR (Rodriguez-Martin & Rodriguez-Gonzalvez, 2019). Experiences of beginning welders regarding VR welding training ergonomics were similar to that of traditional live welding, but it was noted that welding positions in the VE must reflect those in the live environment (Feier & Banciu, 2021). One article examined teachers' experiences from VR welding training and found that teachers faced initial challenges familiarizing themselves with VR welding technology but, once they developed a deeper understanding, appreciated and valued VR (Karstensen & Lier, 2020).

System Development

The third theme identified was *3. System Development*. This theme emerged from six articles that proposed and/or developed a VR welding system (Benson et al., 2016; Chambers et al., 2012; Hadinejad-Roudi et al., 2021; Ismael et al., 2021; Shankhwar & Smith, 2022; Shankhwar et al., 2022). Articles within this theme discussed various immersive and mobile VR systems for inspecting welds, welding, and interacting in welding environments. Accuracy and fidelity of virtual weld penetration and simulation tracking were the main areas of focus for VR system developments (Benson et al., 2016; Chambers et al., 2012; Ismael et al., 2021). Further, all six articles within the *3. System Development* theme concluded that VR welding systems aid in self-learning and learning enhancement (Hadinejad-Roudi et al., 2021; Shankhwar & Smith, 2022; Shankhwar et al., 2022).

System Testing

The final theme, *4. System Testing*, emerged from five articles that evaluated recently developed VR systems (Benson et al., 2016; Hadinejad-Roudi et al., 2021; Ismael et al., 2021; Shankhwar & Smith, 2022; Shankhwar et al., 2022). Researchers tested their respective VR systems' fidelity of feedback (i.e., visual, audial, haptic) and overall accuracy of virtual weld gun tracking (Benson et al., 2016; Ismael et al., 2021). Testing a VR welding system resulted in an increased sense of presence in the VE compared to other VR systems (Shankhwar & Smith, 2022; Shankhwar et al., 2022). A VR system tested by Hadinejad-Roudi et al (2021) was observed to aid in self-learning practices.

Research Recommendation Themes

Research recommendations from the collected articles (*N*=18) were identified and grouped, outlined in Table 3. The most frequent theme, emerging from five articles, was the call for researchers to *1. Improve Fidelity Aspects of VR Welding Training Systems* (Benson et al., 2016; Byrd et al., 2018; Chambers et al., 2012; Shankhwar & Smith, 2022; Shankhwar et al., 2022). More specifically, previous researchers indicate there is a need to improve movement accuracy and for optic, visual, and haptic feedback (Benson et al., 2016; Chambers et al., 2012; Shankhwar & Smith, 2022; Shankhwar et al., 2022). Improving these aspects of VR welding training is intended to ensure the training accurately mimics traditional training.

Another research recommendation theme that emerged from the literature, present in four articles, was a call for future research to *2. Investigate the Effects of VR Technology as a Teaching Tool* (Byrd et al., 2015; Chambers et al., 2012; Rodriguez-Martin & Rodriguez-Gonzalvez, 2019; Wells & Miller; 2020b).

These articles encouraged future research to investigate the sequencing of VR technology implementation. Limited research has examined the various sequencing options for VRI welding training methods and sequencing effects. It was also suggested that the visual cues provided by VR be investigated for learning outcomes and effects (Byrd et al., 2015; Chambers et al., 2012; Rodriguez-Martin & Rodriguez-Gonzalvez, 2019; Wells & Miller; 2020b).

The third research recommendation theme, emerging from two articles, was for future research to use VR technology to *3. Compare Live Weld Performances to Virtual Weld Performances* (Byrd et al., 2015; Wells & Miller, 2020b). These articles suggested that VR weld performances be compared to live weld performances to determine if VR accurately reflects the live welding process. Research that compares a welder's virtual performance to their live performance could identify if significant differences exist between the two.

The fourth research recommendation theme, *4. Explore Alternative Weld Configurations and Processes*, emerged from three articles (Chambers et al., 2012; Byrd et al., 2015; Wells & Miller, 2020b). These articles highlighted the importance of investigating the performance of more complex weld positions and configurations (e.g., 2G, 4F, 4G), as well as different weld processes (e.g., Shielded Metal Arc Welding, Fluxed Core Arc Welding, Gas Tungsten Arc Welding). Future research investigating these outcomes of utilizing VR welding training for these weld configurations and processes would lead to a deeper understanding of the potential applications of VR technology in the welding industry.

The fifth research recommendation theme, *5. Incorporate VR Training into Welding Training Programs,* emerged from two articles (Chung et al., 2020; Huang et al., 2020). It was recommended that VR technology should be incorporated into welding training programs and investigated for learning outcomes and uses. Currently, research that evaluates the implementation of VR training into CTE, trade school, and welding training programs does not exist.

This review resulted in an emerging theme, emerging from one article, *Measure the Effects of VR HMDs on Welder Comfort* (Feier & Benciu, 2021). There currently exists no research that investigates the effect of VR HMDs on a welder's ability to perform, nor on their comfortability. HMDs, depending on their weight, shape, and size, can affect the user in their virtual environment. Therefore, this article suggests that future research determine if a significant impact upon welder comfort and performance is made by the VR HMDs.

Table 3.

Research Recommendation Themes for Virtual Reality (VR) Welding Literature Analysis, Theme Descriptions, and Number of Articles Categorized into Themes (N=18)

Theme[1]	Description	Articles (*n*)
1. Improve VR system fidelity	Accuracy of optic, visual, or haptic feedback; system tracking of virtual weld gun; accuracy of weld pools	5
2. Investigate VR as a teaching tool	Sequencing of VR technology implementation; effects of virtual cue use	4
3. Compare live weld performances to virtual weld performances	Determining if VR accurately represents the live process of welding	2
4. Explore alternative weld processes and configurations	Incorporating complex weld configurations and processes into VR welding investigations	3
5. Incorporate VR training into welding training programs	Exploring the effects of utilizing VR in CTE, trade schools, and welding programs	2

[1]This table does not include the emerging research recommendation theme, identified by researchers in one of the collected articles

Practitioner-Based Recommendation Themes

Practitioner-based recommendations from the collected articles were identified and grouped (*N*=18), outlined in Table 4. The most prevalent theme that emerged in four articles from the collected literature was *1. Instructors Should Develop Skills to Implement and Use VR* in their training (Huang et al., 2020; Wells & Miller 2020a; Wells & Miller, 2020b; Wells & Miller, 2022). These articles suggest that instructors who have knowledge of how VR can be utilized can accurately integrate it in their programs. Professional development workshops, seminars, and summer classes are potential opportunities for instructors to gain more experience and knowledge of VR welding technology (Wells & Miller, 2020b; Wells & Miller, 2022).

The second theme, which emerged from three articles, was *2. Promoting the Use of VR as a Support Teaching Tool*, specifically mobile VR technology (Byrd et al., 2015; Ismael et al., 2021; Wells & Miller, 2020b). This practitioner-based recommendation theme suggests that VR is not a replacement for welding training, but as a supplemental teaching tool. Specific suggestions are that mobile VR can be a cost-effective method for integrating VR into training (Ismael et al., 2021).

The third practitioner-based recommendation theme that emerged was *3. Use Correct Welding Positions When Welding in VR* (Feirer & Bancui, 2021; Stone et al., 2013). These articles suggested that welders undergoing any form of welding training, especially virtual, should use the correct live welding positions. This process ensures the VR welding training will more accurately simulate live welding conditions.

This review resulted in one emerging theme for practitioner-based recommendations, *Utilize VR Technology to Evaluate New and Experienced Welders* (Byrd et al., 2015). Welding program directors and instructors examining welders' skills in a VE could potentially have more in-depth and accurate understandings of a welder's performance abilities if they implemented VR training. By evaluating beginning welders through VR training systems, welding instructors have the potential to identify dexterous and physical abilities (Byrd et al., 2015).

Table 4.
Practitioner-Based Recommendation Themes for Virtual Reality (VR) Welding Literature Analysis, Theme Descriptions, and Number of Articles Categorized into Themes (N=18)

Theme[1]	Description	Articles (*n*)
1. Instructors Should Develop Their Own VR Technology Skills	By understanding the uses of VR technology, instructors can correctly implement it into their programs	4
2. Use VR As a Support-Teaching Tool, Specifically Mobile VR Technologies	Mobile VR technologies can be cost-effective options for a support teaching tool	3
3. Use Correct Welding Positions When Welding in VR	Correct welding positions will reinforce good performance in live welding settings	2

[1]This table does not include the emerging practitioner-based recommendation theme, identified by researchers in one of the collected articles

Discussion and Recommendations

Through this literature review, we collected and examined existing research that investigated the benefits, limitations, and outcomes of implementing VR technologies into welding training settings. The objectives for this review were to: 1) Determine the number of existing research articles published between 2012-2022 regarding immersive VR technology implementation in the welding training and education sector; 2) Determine which research questions and topics are prevalent within the existing literature; and 3) Identify and interpret the key themes prevalent within the existing literature's recommendations for practice and future research. Literature collected and analyzed were peer-reviewed research articles published between 2012 and 2022. Articles were analyzed to determine prevalent themes across research topics, research recommendations, and real-world practice recommendations. The Engagement in Blended Learning Environments concept served as the conceptual framework for our study (Halverson & Graham, 2019). This concept describes how a learners' engagement level depends on the cognitive and emotional energy they dedicate to their lesson or activity. The more cognitive and emotional energy used, the more likely the learner is to obtain certain academic achievements and satisfaction.

A total of 18 articles were included in this literature review. We identified four major research topic themes across the existing literature: *1. Comparison of Approaches, 2. VR as a Teaching Tool, 3. System Development,* and *4. System Testing.* The first research theme, *1. Comparison of Approaches*, which compared and contrasted different aspects and outcomes between welding training methods, emerged from four articles. Three of these articles investigated the differences between full VR welding training methods and traditional live welding training methods (Liang et al., 2014; Shankhwar & Smith, 2022; Shankhwar et al., 2022), and one investigated the differences between a full VR welding training method against a VRI training method (Byrd et al., 2018). Findings from these articles support the Engagement in Blended Learning Environments concept in that VR systems are used as supplemental learning experiences, rather than replacements for live welding.

The second research theme, *2. VR as a Teaching Tool* emerged from 14 of the articles and encompassed research investigating the teaching aspects of VR technology implementation. This theme included three sub-themes: *2.1 Performance Outcomes, 2.2 User Perceptions,* and *2.3 User Experiences*. These articles are rooted in the Engagement in Blended Learning Environments concept as they evaluate the learning aspects of VR welding systems. These articles provide a deeper understanding of the perceptions and experiences of users from utilizing the VR welding blended learning environment, developing a framework for how VR can be used in blended learning and how it is perceived by various users (i.e., trainees, instructors). Though some users are optimistic of VR's potential to benefit welding education and training, some perceptions report feelings of wariness or indifference. Research that helps to better understand why these perceptions exist will enhance our use of VR as a blended learning tool.

The third research theme, *3. System Development,* emerged from six articles that developed and evaluated VR welding systems (Benson et al., 2016; Chambers et al., 2012; Hadinejad-Roudi et al., 2021; Ismael et al., 2021; Shankhwar & Smith, 2022; Shankhwar et al., 2022). VR system functions, advantages, limitations, and potential uses are discussed throughout these articles, though these discussions are limited to whatever specific VR system is being used for that article. The fourth and final research theme, *4. System Testing,* emerged from five articles that tested their respective VR system for fidelity, accuracy, tracking ability, and sense of presence (Benson et al., 2016; Hadinejad-Roudi et al., 2021; Ismael et al., 2021; Shankhwar & Smith, 2022; Shankhwar et al., 2022). Many of these system development and testing studies are aimed at investigating similar systems and similar functions. Therefore, research- and institution-collaboration would greatly benefit the welding education and training research area and solidify the foundations of VR welding system development and testing.

Prevalent themes across the research and practitioner-based recommendations were also identified. Future research recommendation themes include recommendations to improve VR welding systems' fidelity and accuracy of tracking, investigate VR technology as a teaching tool, compare live welds to virtual welds, explore alternative weld processes and configurations, incorporate VR technology into welding training programs, and to measure the effects of VR HMDs. Practitioner-based recommendations include suggestions for welding instructors to develop their own knowledge of VR technologies, to use VR systems to evaluate welder performance, to use VR as a supportive teaching tool, and to promote the use of correct welding positions when virtually welding.

From this literature review, it is clear that there are gaps in the existing research and, therefore, recommendations can be made for future research focused on VR welding training. The first gap is the lack of insight into how virtual cues impact welding training and the training outcomes. Multiple researchers (Byrd et al., 2015; Chambers et al., 2012; Wells & Miller. 2020b) recommended that the virtual parameter cues available in VR welding training should be investigated. Virtual parameter cues can be engaged to aid users in correcting their mistakes, potentially leading them to develop problem-solving skills in the welding environment. Research that seeks to directly understand the effects of virtual cue implementation in a Blended Learning Environment, such as that of virtual welding training, does not currently exist. It is recommended that the effects and outcomes of virtual, visual, and audial cues be investigated and compared. Future research is recommended to explore these areas of interest to address the existing gaps in welding education literature and promote the advancement of welding training development.

The second gap is the lack of research that involves the implementation of VR technology into welding training or education, investigating the effects of VR as a supportive training and/or teaching tool. Three studies suggested that VR be used as a supplemental tool, and few studies examine the effects of such integration. Specifically, it is recommended that these studies occur over an extended period (i.e., six weeks), considering many studies are conducted over short, limited time periods such as hour-long or four-week-long trainings (Byrd et al., 2018; Wells & Miller, 2020a). In the articles reviewed, the weld process and configurations performed were less complex. Byrd et al. (2015) and Stone et al. (2013) utilized the Shielded Metal Arc Welding and Gas Metal Arc Welding processes, two of the most common welding processes, and the 2F, 1G, 3F, and 3G configurations, which are relatively simple compared to other weld configurations. Future research should investigate the various welding processes (e.g., Shielded Metal Arc Welding, Gas Metal Arc Welding, Gas Tungsten Arc Welding, Flux Cored Arc Welding), welding configurations (e.g., T-joint, flat, groove, lap, pipe), and welding positions (e.g., horizontal, vertical, overhead). Understanding if and how VR welding simulations can be useful for training different welding processes and configurations will develop a better framework for its use in successful blended learning environments.

The final gap we identified within the existing literature is there exists no in-depth understanding of the barriers to VR technology integration in welding training. Karstensen and Lier (2020) gathered the perceptions of two instructors and their two department heads regarding VR technology and Wells and Miller (2020a) gathered the perceptions of 90 SBAE instructors; however, further research is needed from other stakeholders to establish a true understanding of barriers that exist for VR welding training. Specifically, future research must explore the decision-making factors for welders, welding instructors, and teachers when considering VR technology implementation to highlight areas in which aid can be provided to these instructors for enhancing their teaching methods within these Blended Learning Environment opportunities.

Finally, in the process of analyzing the collected articles, we identified two articles that contained plagiarized literature and data pulled directly from articles published by other authors. There were three articles that were published in predatory journals that included incomplete sections, several misspelled words, and other red flags that made identification in a predatory journal obvious. These articles were immediately excluded from the review; it is therefore recommended that researchers adhere to the guidelines of ethical research practices and maintain efforts to investigate the credibility of the journals they are publishing in. We recommend that future researchers conducting synthesis of literature research report plagiarism issues with the journal editors.

References

Adams, D., Sayyad, A., & Paliwal, S. (2022). *Welding electrode: Chart and selection*. Weld Guru. Retrieved September 13, 2022, from https://weldguru.com/welding-electrode/

American Welding Society. (2022). AWS - highlighting the welding workforce demand in the U.S. Welding Workforce Data. Retrieved May 26, 2022, from https://weldingworkforcedata.com/

Benson, R. A., Krishnan, V. L., Reddy, T. A., & Prasad, G. R. K. (2016). Virtual reality-based welding training simulator. *International Journal Circuit Theory and Applications*, *9*, 1235-1243.

Buel, Z. (2021). *How old are welders? investigating the "skilled trades shortage"*. Tulsa Welding School. Retrieved December 15, 2021, from https://www.tws.edu/blog/welding/how-old-are-welders-investigating-the-skilled-trades-shortage/

Byrd, A. P., Stone, R., & Anderson, R. G. (2015). The use of virtual welding simulators to evaluate experienced welders. *The Welding Journal, 94*, 389-s-395-s. https:/doi.org/ 20.500.12876/44402

Byrd, A. P., Stone, R. T., & Anderson, R. G. (2018). Dexterity: An indicator of future performance in beginning welders. *Career and Technical Education Research, 43*(2), 195-213. https://doi.org/10.5328/cter43.2.195

Chambers, T. L., Aglawe, A., Reiners, D., White, S., Borst, C. W., Prachyabrued, M., & Bajpayee, A. (2012). Real-time simulation for a virtual reality-based MIG welding training system. *Virtual Reality*, *16*(1), 45-55. https://doi.org/10.1007/s10055-010-0170-x

Chung, C.-C, Tung, C.-C., & Lou, S.-J. (2020). Research on optimization of VR Welding Course Development with ANP and satisfaction evaluation. *Electronics*, *9*(10), 1673. https://doi.org/10.3390/electronics9101673

Dalto, L., Benus, F., and Balet, O. (2010). The use and benefits of virtual reality tools for the welding training. *63rd Annual Assembly & International Conference of the International Institute of Welding*, Istanbul, Turkey

Feier, A. I., & Banciu, F. V. (2021). Ergonomic aspects of real and virtual welding tools. *Acta Technica Napocensis-Series: Applied Mathematics, Mechanics, And Engineering*, *64*(1-S1), 117-126. https://doi.org/10.1051/matecconf/202134311014

Hadinejad-Roudi, A., Fesharakifard, R., Rezaei, S. M., & Nahvi, A. (2021). Virtual manual arc welding by real-time process simulation for an effective training. *AUT Journal of Mechanical Engineering*, *5*(1), 121-140. https://doi.org/10.22060/AJME.2020.17800.5875

Halverson, L.R., & Graham, C.R. (2019). Learner engagement in blended learning environments: A conceptual framework. *Online Learning, 23*(2), 145-178. https://doi.org/10.24059/olj.v23i2.1481

Hasan, R. B., Aziz, F. B. A., Mutaleb, H. A. A., & Umar, Z. (2017). Virtual reality as an industrial training tool: A review. *Journal of Advanced Scientific Research, 29*(1), 20-26.

Huang, C.-Y., Lou, S.-J., Cheng, Y.-M., & Chung, C.-C. (2020). Research on teaching a welding implementation course assisted by Sustainable Virtual Reality Technology. *Sustainability*, *12*(23), 10044. https://doi.org/10.3390/su122310044

Ilyashenko, L. K., Smirnova, Z. V., Vaganova, O. I., Chelnokova, E. A., & Kaznacheeva, S. N. (2019). Methods of conducting practical training on the subject power sources for welding. *International Journal of Mechanical Engineering and Technology*, *10*(02), 908-917.

Ismael, M., Mohamed, F., Siang, C. V., Mokhtar, M. K., & Azizo, A. S. (2021). VR Welding Kit. *JACTA*, *3*(1).

Ipsita, A., Erickson, L., Dong, Y., Huang, J., Bushinski, A. K., Saradhi, S., Villanueva, A. M., Peppler, K. A., Redick, T. S., & Ramani, K. (2022). Towards modeling of virtual reality welding simulators to promote accessible and scalable training. CHI Conference on Human Factors in Computing Systems. https://doi.org/10.1145/3491102.3517696

Karstensen, S., & Lier, A. R. (2020). Virtual welding: A didactic perspective. *Nordic Journal of Vocational Education and Training*, 95–107. https://doi.org/10.3384/njvet.2242-458x.2010195

Kovar, K. A., & Ball, A. L. (2013). Two decades of agricultural literacy research: A synthesis of the literature. *Journal of Agricultural Education*, *54*(1), 167-178. https://doi.org/10.5032/jae.2013.01167

Kulkarni, B., Banerjee, R., & Raghunathan, R. (2022). Why students should be taught differently: learner characteristics, learning styles and simulation performance. *Simulation & Gaming*, *53*(1), 56–74. https://doi.org/10.1177/10468781211065809

Liang, X., Kato, H., Hashimoto, N., & Okawa, K. (2014). Simple virtual reality skill training system for manual arc welding. *Journal of Robotics and Mechatronics*, *26*(1), 78-84. https://doi.org/10.20965/jrm.2014.p0078

Lincoln Electric. (2022). *Welding training systems curriculum*. Welding Training System Curriculum. Retrieved November 4, 2022, from https://www.lincolnelectric.com/en/Education/Training-Programs/Education-Products/Curriculum/Welding-Training-System-Curriculum

Miller Electric Mfg LLC. (2005). *Repair costs for welders*. Miller Welding Discussion Forums. Retrieved September 13, 2022, from https://forum.millerwelds.com/forum/welding-discussions/6094-repair-costs-for-welders

Rodríguez-Martín, M., & Rodríguez-Gonzálvez, P. (2019). Learning methodology based on weld virtual models in the mechanical engineering classroom. *Computer Applications in Engineering Education*, *27*(5), 1113-1125. https://doi.org/10.1002/cae.22140

Shankhwar, K., & Smith, S. (2022). An interactive extended reality-based tutorial system for fundamental manual metal arc welding training. *Virtual Reality*, 1-20. https://doi.org/ 10.1007/s10055-022-00626-6

Shankhwar, K., Chuang, T. J., Tsai, Y. Y., & Smith, S. (2022). A visuo-haptic extended reality–based training system for hands-on manual metal arc welding training. *The International Journal of Advanced Manufacturing Technology*, 1-17. https://doi.org/10.1007/s00170-022-09328-4

Stone, R. T., McLaurin, E., Zhong, P., & Watts, K. (2013). Full virtual reality vs. integrated virtual reality training in welding. *Welding Journal, 92*(6), 167-174.

Wells, T., & Miller, G. (2020a). Teachers' opinions about virtual reality technology in school-based agricultural education. *Journal of Agricultural Education*, *61*(1), 92-109. https://doi.org/10.5032/jae.2020.01092

Wells, T., & Miller, G. (2020b). The effect of virtual reality technology on welding skill performance. *Journal of Agricultural Education*, *61*(1), 152-171. https://doi.org/ 10.5032/jae.2020.01152

Wells, T., & Miller, G. (2022). Students' perspectives on using virtual reality technology in a university-level agricultural mechanics course. *Journal of Agricultural Education*, *63*(2), 17-36. https://doi.org/10.5032/jae.2022.02017

White, S., Reiners, D., Prachyabrued, M., Borst, C., & Chambers, T. (2010). Virtual reality welder training. *IS&T/SPIE Electronic Imaging*. San Jose, California, United States. https://doi.org/10.1117/12.840473

Whitney, S. & Stephens, A. (2014). Use of simulation to improve the effectiveness of army welding training. *Defence Science and Technology Organisation, AR-016-018.*