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Virtual Reality Integrated Welder Training

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Abstract
Training in the welding industry is a critical and often costly endeavor; this study examines the training potential, team learning, material consumption, and cost implications of using integrated virtual reality technology as a major part of welder training. In this study, 22 participants were trained using one of two separate methods (traditional training (TT) and virtual reality integrated training (VRI)). The results demonstrated that students trained using 50% virtual reality had training outcomes that surpassed those of traditionally trained students across four distinctive weld qualifications (2F, 1G, 3F, 3G). In addition, the VRI group demonstrated significantly higher levels of team interaction, which led to increased team-based learning. Lastly, the material cost impact of the VRI group was significantly less than that of the TT group even though both schools operated over a full two-week period.

Keywords
human factors, shielded metal arc welding, virtual reality, welder training, mechanical engineering

Disciplines
Industrial Engineering | Mechanical Engineering | Systems Engineering

Comments
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Virtual Reality Integrated Welder Training

A scientific evaluation was performed of training potential, cost effectiveness, and implication for effective team learning

BY R. T. STONE, K. WATTS, AND P. ZHONG

ABSTRACT

Training in the welding industry is a critical and often costly endeavor; this study examines the training potential, team learning, material consumption, and cost implications of using integrated virtual reality technology as a major part of welder training. In this study, 22 participants were trained using one of two separate methods (traditional training (TT) and virtual reality integrated training (VRI)). The results demonstrated that students trained using 50% virtual reality had training outcomes that surpassed those of traditionally trained students across four distinctive weld qualifications (2F, 1G, 3F, 3G). In addition, the VRI group demonstrated significantly higher levels of team interaction, which led to increased team-based learning. Lastly, the material cost impact of the VRI group was significantly less than that of the TT group even though both schools operated over a full two-week period.

Introduction

Welding is a skill, and as such requires that its practitioners be trained to a standard; this kind of training requires time, money, and talent. For nearly as long as modern welding has existed, innovators have been exploring new ways to increase the effectiveness of its training.

Currently, computer-based virtual reality (VR) training (CS Wave) and immersive VR training systems (VRTEX™, ARC+) have generated interest because they have the potential to reduce training costs (Refs. 1–3). However, cost savings is only beneficial if the result is a competent welder who is trained in a timely manner.

Prior to this study, the direct training impact of using VR technology as an integrated part of weld training has not been evaluated. Published works pertaining to VR technology in welding focus primarily on the training technology and its development, not the development of the trainee (Refs. 4, 2). Many studies have focused on general use of VR in training operations and results are far from conclusive. Some studies have shown that the use of VR technology leads to reduced learning and transfer of skills (e.g., Refs. 5, 6). Other studies have shown that the use of VR technologies in training is not significantly different from real-world training (e.g., Refs. 7, 8). Many studies have found that the use of VR technologies leads to a superior transfer of skills when compared to traditional methods (Refs. 9–12). There are many reasons for this diversity of findings, like the methodology used for investigating the transfer of training (Ref. 13). More commonly, however, it is the fidelity of the different VR machines evaluated and the degree to which the individual technologies were suited to their tasks that account for the major sources of inter-study variation (Refs. 14, 15).

Modern technology has evolved to a point such that some VR systems have the ability to create high-fidelity immersive environments (due in large part to advanced physic engines and graphics-rendering capabilities) coupled with an ability to achieve realistic kinesthetic movements (due to magnetic displacement technologies allowing for 6 depth-of-field movements). These aspects of current VR welding simulators allow users to utilize kinesthetic and cognitive learning in a way never before available in the virtual environment. In addition, some VR systems such as the VRTEX™ 360 allow users to work in teams, with one member observing welding progress while the other conducts the actual VR welds. This kind of system further encourages team-based interaction and learning among users. It must be noted that the authors hold the VRTEX 360 as an example of a VR system capable of providing a level of realism and kinesthetic feedback appropriate for this study. The authors do not endorse this product over others that have the beforementioned capabilities.

Prior to conducting this investigation, the authors hypothesized the following: 1) VR integrated training would result in superior training outcomes when compared to traditional methods, 2) the use of a state-of-the-art VR system would lead to increased levels of team interaction and learning, and 3) weld training conducted with VR integrated technology would be significantly less expensive than training conducted using traditional means.

KEYWORDS

Virtual Reality
Welder Training
Human Factors
Shielded Metal Arc Welding

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Background

Transfer of Training Paradigm

The simplest way to evaluate the amount of learning that has taken place during the course of a training program is to measure performance prior to training and compare it with performance measures after training has taken place (Ref. 16). Often, training performance is measured in terms of both operation completion time and accuracy. These measures can be translated into training effectiveness ratios (TER) that enable comparison between training conditions.

The transfer of training paradigm requires a minimum of two groups of trainees, functioning as an experimental group and a control group (Ref. 17). The group(s) given a new instructional device (or alternative method of training) is the experimental group(s). The group given the standard training (or no training) is the control group. In this experiment, the experimental group used VR training technology 50% of the time and traditional training the remainder of the time (VRI), whereas the control group used traditional means of training 100% of the time (TT). To employ the transfer of training paradigm effectively, it is necessary to select appropriate

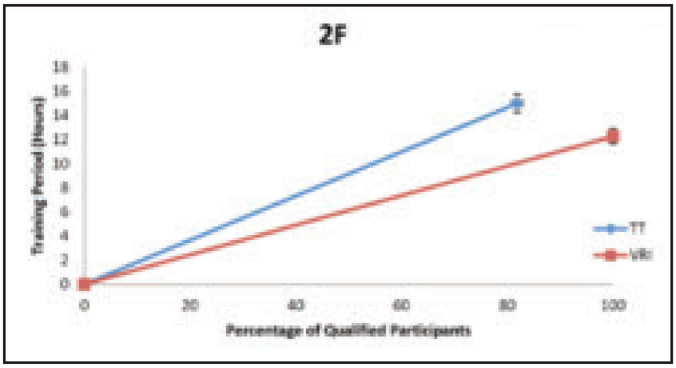

Fig. 1 — Training performance and time outcomes for training in the 2F position.

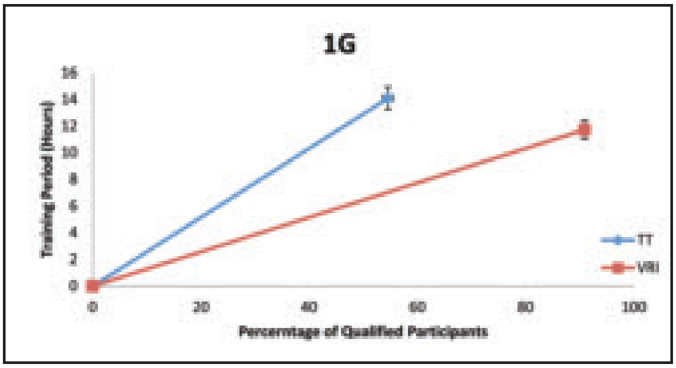

Fig. 2 — The four certifiable weld positions in this study, depicted in order of increasing difficulty.

measurements to determine the extent to which training has been effective. In the case of this study, the qualification rate (the number of welders qualified for a specific position) was used as the primary performance measure. The performance of the control group, measured in terms of time and qualification rate, was used as a baseline. A positive transfer effect occurs when the experimental group performs as well as or better than the control group. In the transfer of training paradigm, the control group is automatically assigned a TER of zero. A TER greater than zero represents a positive transfer effect; while a TER less than zero indicates a negative transfer effect. The percent transfer is the absolute difference between control and experimental group performance. The transfer of training paradigm is an effective tool in the assessment of alternative training methods, and has commonly been used to determine the transfer effect between virtual reality, augmented reality, and real training environments (e.g., Refs. 15, 18–20) particularly in laparoscopic surgery (e.g., Refs. 21, 22) as well as in aircraft simulation (Refs. 23, 24).

Team Interaction and Learning

Team learning occurs when multiple individuals carry out activities that enhance the acquisition and development of competencies in all team members. Research has shown that students who learn in team situations have a stronger tendency to learn from past experiences and are more likely to take actions that lead to continuous development (Ref. 25). This has been documented many times in various settings including many college classrooms (Refs. 26, 27). In this study, the team learning questionnaire (TLQ) that was developed and validated by Breso et al. in 2008 formed the basis for our team learning evaluation (Ref. 28). The TLQ evaluation was modified so that the questions and content were specific to the domain of weld training. The TLQ method of evaluation tracked three key dimensions of team learning and interaction that were relevant to this study: 1) Continuous Improvement Seeking (the degree to which a team can learn from previous experiences); 2) Dialogue Promotion and Open Communication (the degree to which open and honest communication is encouraged and takes place within a team); and 3) Collaborative Learning (the degree to which team members are seen and used as sources of knowledge by the rest of the team). Each dimension consists of a series of questions, which the participant answers on a five-point scale (the higher the rating for a given question the more positive the participant feels about the team learning for that question). In addition to TLQ, the authors of this study used continuous video and auditory recordings to assess the amount of time students spent interacting within the weld booths.

Experiment

Training Facilities and Equipment

Both a traditional and a VR welding facility were constructed on the Iowa State University campus. The traditional facility housed six welding booths. Each booth was equipped with the following: a new Lincoln Electric Power MIG 350MP welding machine with shielded metal arc welding (SMAW) attachments, two autodarkening welding helmets, multiple sets of welding jackets and gloves, power grinders, slag hammer, wire brushes, welding table, quenching buckets, and other miscellaneous welding equipment. The welding facility was stocked with an ample supply of runoff tabs, flat stock plates, groove plates, and 7018 electrodes.

The VR weld training facility was located one floor below the traditional facility and housed weld booths of the same size and dimensions as their traditional counterparts. Each booth contained a new VR welding trainer with SMAW attachments and multiple sets of welding jackets and gloves. The VRTEX 360 trainer was chosen because it is the highest fidelity VR simulator currently available, and has design features that the authors felt would greatly affect team-based learning.

Certified Welding Inspector

Achieving the rank of AWS Certified Welding Inspector (CWI) represents a base standard for instructor capability; as such, the CWI capability was considered to be a controlled variable. However, it is important to note that individual teaching styles and capabilities are an important influencing factor in knowledge acquisition. For this reason, the experimenters observed four different CWIs at three different welding schools so as to learn what individual differences existed between them. Analysis revealed that the major factor was overall experience in teaching (how long they have been instructing). For this reason, the experimental protocol of this study called for a CWI with at least 15 years of active teaching experience.

There was one paid CWI (who had 15 plus years of experience) used in this experiment to train participants in both the TT and VRI groups. All CWI activities were closely monitored by the experimenter to ensure that the same style of interaction and information exchange was maintained between the CWI and participants in both groups. Lastly, poststudy questionnaires sent to participants revealed that participants in the TW group rated their instructor's capabilities as a teacher at 4.2/5, participants in the VRI group rated their instructors as 3.8/5. This indicated that the perception of the instruction between the two groups was not significantly different. The controls for the CWI were appropriate; if an alternative CWI with similar experience were to have been used the overall outcome would be expected to remain the same.

Participants

There were 22 participants in total (21

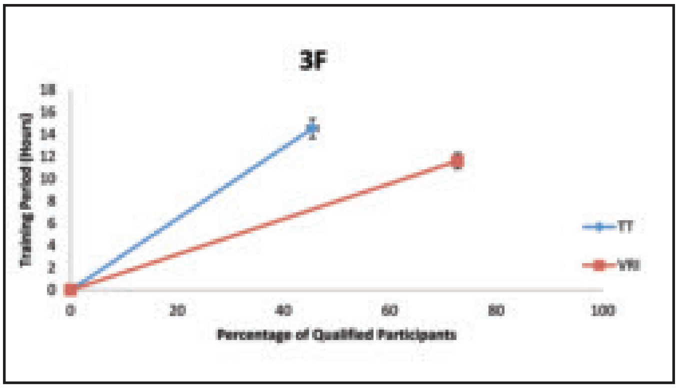

Fig. 3 — Number of certifications awarded by weld type (in order of increasing difficulty).

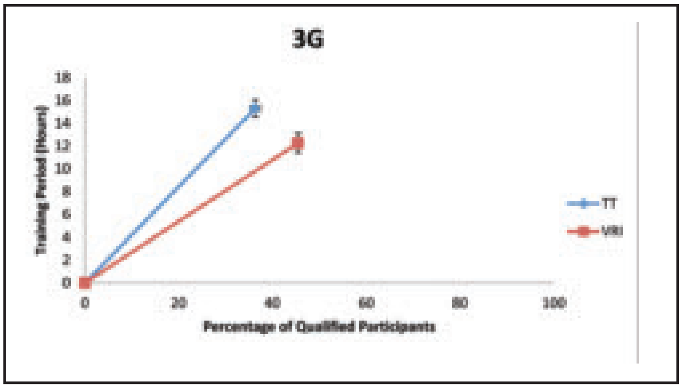

Fig. 4 — Mean training times by weld type (in order of increasing difficulty).

males and one female). All participants committed to 80 training hours over the course of two weeks. Participants were randomly assigned to one of two groups. Group one (VRI) subjects were trained with 50% VR + 50% traditional training, whereas group two (TT) subjects were trained using only the traditional training system. Participants in this study were screened to ensure little to no welding experience prior to the beginning of this study. The four participants with some previous experience were evenly distributed between the two experimental groups. Participants in the TT and VRI groups had an average age of 44 and 41 years, respectively.

Independent and Dependent Variables

The primary independent variable in this experiment was training type at two levels, representing the type of interface tested: Traditional Weld Training (TT) and 50% Virtual Reality Training (VRI).

There were five major dependent measures in this investigation: percentage transfer, training effectiveness ratio (TER), team learning, material consumption, and cost effectiveness. Percentage transfer and TER are both training potential measures. As such, both were based on the outcomes of participant qualification rates and training time. Qualification rates were evaluated for each of four different weld positions tested in this study, including the 2F, 1G, 3F, and 3G positions. Training time was defined as the total amount of time taken to train for a qualification. Team learning was measured using the TLQ questioner and follow-up video evaluation. Material consumption and cost effectiveness were functions of total plate and electrodes.

Experimental Procedure

Prior to experimentation, all participants gave informed consent, followed by individual screening tests to ensure that they possessed normal visual acuity, depth perception, and hearing. Upon completion of screening tests participants were randomly assigned to either the VRI or the TT experimental group. The TT group trained at ISU for two weeks, and then one week later the VRI group trained for two weeks.

In the traditional welding school (TT group), participants were trained in the principles and practical application of welding techniques starting with the simplest position (2F), and proceeding through to the most difficult (3G). The maximum amount of training time allotted for teaching was fixed; this time included formal lectures and practical lab training conducted by an AWS Certified Welding Inspector (CWI). The CWI was responsible for evaluating welds to determine whether or not a participant was ready to be tested prior to the end of his or her total allotted training time. Following the training for each qualification, participants were given their test plate. If the test plate for the qualification test passed the CWI's visual inspection, it was sent to an independent laboratory for structural testing. Qualification for certification was based on the results of this structural testing. Immediately following the qualification tests for all four welds, participants were administered TQL evaluations.

In the VR integrated welding school (VRI), the experiment was conducted in the same basic manner as the previous group. Both TT and VRI groups were given the same overall training time opportunity for each weld type. The major difference between traditional training and VR integrated training was in the training system itself. Participants in the VRI group spent only 50% of their time training (lectures and practical lab training) under the direction of an AWS CWI for each weld type. The remaining 50% of their time was spent training on the VR system. During VR training time, the participants (in pairs) used the VR system to conduct virtual welds of each of the four weld types on which they would be tested. If the participants were able to earn a machine-generated quality score of 85% at least twice in a row for a weld, they were permitted to discontinue their VR training time early.

Results

Training Potential

Training potential is defined by both the percent transfer and the transfer effectiveness ratio (TER). These measures encompass both the differences in certification outcomes between the groups as well as the differences in absolute training time between the groups.

Figure 1 shows the training differences in terms of qualification rate and training time for the 2F position. Participants in the VR50 group (q. rate = 100%, M time = 12.27 h) outperformed the TW (q. rate = 81.8%, M time = 15.05 h) group in terms of both qualification rate and training time. The VRI group was found to have a 22.2% positive transfer and a TER of 1.81 when compared to the TT group.

Figure 2 shows the training differences in terms of qualification rate and training time for the 1G position. Participants in the VRI group (q. rate = 90.1%, M time = 11.72 h) outperformed the TT (q. rate = 54.5%, M time = 14.09 h) group in terms of both qualification rate and training time. The VRI group was found to have a 66.7% positive transfer and a TER of 5.68 when compared to the TT group.

Figure 3 shows the training differences in terms of qualification rate and training time for the 3F position. Participants in the VRI group (q. rate = 72.7%, M time = 11.60 h) outperformed the TT (q. rate = 45.5%, M time = 14.54 h) group in terms of both qualification rate and training time. The VR50 group was found to have a 60% positive transfer and a TER of 5.17 when compared to the TW group.

Figure 4 shows the training differences in terms of qualification rate and training time for the 3G position. Participants in the VRI group (q. rate = 45.5%, M time = 12.25 h) outperformed the TT group (q. rate = 36.4%, M time = 15.31 h) in terms of both qualification rate and training time. The VRI group was found to have a 25% positive transfer and a TER of 2.04 when compared to the TT group.

Team Interaction and Learning

Team interaction and learning was assessed across three dimensions [1) Continuous Improvement Seeking, 2) Dialogue Promotion and Open Communication, and 3) Collaborative Learning], each representing a different aspect of cognitive capability. Interaction styles were evaluated using video-based interaction analysis.

The VRI (M score = 4.47) group was not found to be significantly distinctive from the TT (M score = 4.14) group in terms of continuous improvement seeking ($T_{0.05,\,1,\,20} = -1.617$, $P = 0.121$). Hence, both groups demonstrated a very strong desire to learn from their experiences and to use what they learned to improve as individuals and as a team. This finding indicates that the participants in both groups were equally willing to learn in the team context.

The VRI (M score = 4.63) group was found to be significantly more developed in terms of Dialogue Promotion and Open Communication than was the TT group (M score = 3.85) ($T_{0.05,\,1,\,20} = -4.542$, $P < 0.001$). Students in the VRI group were significantly more likely to engage in task-specific communication with their team member than were students in the TT group. Video analysis revealed that the VRI group spent an average of 32% of their shared-booth virtual reality training time engaged in training-relevant discussion (this discussion was primarily related to the screen-observing student directing the student performing a virtual weld). This can be compared to only 17% of the time spent in training-related discussion when sharing a booth in the real world training facility (this discussion occurred primarily when the team member was in between passes). Video analysis demonstrated that participants in the TT group engaged in training-relevant discussion an average of 10% of the time when sharing a booth in the real-world training facility (this discussion occurred when the team member had completed a pass or a full plate).

The VRI (M score = 4.73) group was found to be significantly more developed in terms of Collaborative Learning than was the TT group (M score = 3.30) ($T_{0.05,\,1,\,20} = -8.318$, $P < 0.001$). Students in the VRI viewed their team members as sources of knowledge to a greater extent than did students in the TT group. The higher the level of collaborative learning in a team the greater the likelihood that positive teamwork interaction took place and they learned from one another.

Material Consumption

Real-World Material Usage

The VRI group used significantly less flat plates than the TT group ($T_{0.05,\,1,\,20} = 4.607$, $P < 0.001$). The VRI group used 210 flat plates compared to the TT group, which used 288.

Also, the VRI group used significantly less groove plates than did the TT group. The VRI group used 50 groove plates compared to 63 for the TT group ($T_{0.05,\,1,\,20} = 2.711$, $P = 0.013$). Similarly, the VRI group used significantly less electrodes than did the TT group, 111.2 lb for the VRI group compared to 187.6 lb for the TT group ($T_{0.05,\,1,\,20} = 8.958$, $P < 0.001$).

Virtual-World Stock Material Usage

The VRI group used a significantly larger amount of overall flat plates (when considering both virtual- and real-world plates) than the TT group. The VRI group used a total of 550 combined (real + virtual) flat plates compared to the 288 real plates the TT group used ($T_{0.05,\,1,\,20} = -12.343$, $P < 0.001$). The VRI group used a significantly larger amount of overall groove plates than did the TT group. The VRI group used a total of 82 combined plates compared to the 63 real plates the TT group used ($T_{0.05,\,1,\,20} = -8.542$, $P < 0.001$). However, the VRI group did not use a significantly larger number of electrodes than did the TT group. The VRI group used 205.2 lb of electrode vs. 187.6 lb used by the TT group ($T_{0.05,\,1,\,20} = -1.386$, $P = 0.181$). The increased plate use in the VRI group reflects the fact that these students were able to conduct more overall welds due to the fact the virtual environment allows for focused welding time without the need for setup, tacking, etc. No difference in electrode usage was discovered primarily because the VR environment does not suffer from sticking and associated electrode abandonment, as does the real-world condition.

Material Costing

The material costs in this study reflect the consumables purchase prices; it must be noted that these prices may vary depending on a company's vendor and purchasing agreements. Additionally, prices reported in this study do not reflect shipping costs. Prices in this study are as follows: flat plate ($2.00 each), preassembled groove plate ($15.00 each), 7018 electrode ($3.09 per pound).

Real-World Cost Implications

When factoring in the costs for the material, the total dollar value of the flat plate used in the VRI group was $420; the flat plate used by the TT group was $576. Similarly, the total dollar value for the VRI groove plate was $750 while the groove plate cost for the TT group was $945. The total dollar value for the amount of electrode used was again less for the VRI group. The electrode dollar value for the VRI group was $343.61, compared to the TT group value of $579.71. When all materials usage is considered, the total materials training cost for the VRI group was $1513.61, compared to $2100.71 for the TT group. This equates to a per-student cost of $137.6 for participants in the VRI group and a per-student cost of $190.97 for participants in the TT group.

Virtual-World Cost Savings

The equivalent virtual cost represents the hypothetical materials cost that would be generated if the virtual machine actually charged for plates and electrodes. The equivalent virtual cost for the flat plate would have been $680. The equivalent virtual cost for the groove plate would have been $1710. The equivalent virtual cost for the 7018 electrodes would have been $290.46. The total equivalent virtual cost savings, when all factors are considered, equate to $2,680.46. That is a per-student savings of $243.68.

Discussion

The study described in this paper aimed to determine the effect of modern VR training technology in the domain of welding. The overall effectiveness of VR integrated training was examined in terms of training potential, team learning, material demand, and cost. These issues will be discussed by addressing the hypotheses of this paper.

The authors' first hypothesis was that VR integrated training would result in superior training outcomes when compared to traditional methods. In all cases, participants in the VRI group had a greater percent transfer and a far superior TER than participants in the TT group. The VRI group was not only able to surpass the TT group in terms of absolute effectiveness, but they were able to do so with a significantly shorter amount of training time.

This finding strongly supports the use of VR integrated training at the 50% level, and supports the first hypothesis.

The second hypothesis stated that the use of the VR system would lead to increased levels of team interaction and learning. The results from the team interaction and learning analysis showed that for the continuous-improvement-seeking dimension there was no significant difference between the two groups. This indicates that there was no difference in participants' desire to perform well and to learn from their experience between the VRI and TT groups. However, the VRI group did have significantly higher values for the dialog and open communication as well as the collaborative learning dimensions. These results confirm this second hypothesis. Moreover, these results indicate participants in the VRI group were much more willing to communicate and lean from their cohorts. The VR machine provided a conduit by which participants not only were more likely to communicate, but were more likely to value the communication and use it to improve their skills. Team learning was a positive factor in the superior training outcomes associated with VR integrated training.

The third hypothesis was that the weld training conducted with VR integrated technology would be significantly less expensive than training conducted using traditional means. The results of cost analysis clearly confirm this hypothesis. For each type of consumable used in this investigation, the total cost of the material was less for the VRI group compared to the TT group. The VR machine allowed students to practice welds without the need to invest time in setup and material-gathering procedures. As such, the students in the VR group had the opportunity to utilize more plates. If the virtual machine had charged for the consumables, the VRI would have cost twice as much, this despite costing markedly less in terms of the real cost of the physical goods. Further, the ability (afforded by the virtual training system) to abandon a poor weld and start over without the consequence of wasted materials could have been greatly beneficial to the welding students. For example, it was often observed that when students in the VRI group were told (by the partner relaying the machine's score) they had a bad root pass, they would often start over with a new plate. From the students' perspective there was no need to worry about wasting steel or losing the time involved in assembly and re-tacking.

Conversely, students in the TT group were less likely to be aware they had a bad root pass, and even when aware they would retain the plate to avoid setup and wasted plate/money. The increased number of practice welds created by students in the VRI group was a likely contributor to their superior percent transfer and TER. The VR system also allowed the participants to focus on the areas of a weld they needed to practice the most. For example, if they needed to practice the root pass, they could start over on a new piece every single time. This activity could not be feasibly replicated using traditional means of training.

Analysis of the VR system's impact on the human operators indicate that there were at least three major attributes that contribute to the success of the VR weld trainer. The first being the fully immersive environments that allow for the manipulation of physical weld tools. This allows the user to develop sensory motor memories that were appropriate for use in real-world welding situations. Second was the use of feed-forward visual overlays and postweld feedback in the VR system that allowed users to improve specific aspects of their welds during training. This level of oversight and guidance is simply not possible during normal weld training due to environmental factors and time constraints. The third and final attribute was the increased volume of practice weld achievable in the VR environment. By eliminating material transfer and setup times, participants in the VRI group were able to gain more practical experience by spending more time in the commission of a weld than their real-world counterparts. Hence, a successful VR solution should incorporate these key characteristics.

The authors' future work will include a 100% VR weld school. The experiment will be conducted in a similar fashion to the current study, with the exception being that the CWI will only oversee testing as opposed to conducting instructional operations. This study will aid in further understanding of the effectiveness of VR for weld training.

Conclusions

The results of this study clearly show the direct benefits of using virtual reality integrated training in the domain of welding. The students in the VRI group demonstrated vastly superior training outcomes when compared to their traditionally trained (TT) counterparts. Following are two factors that are associated with this outcome: 1) the significantly higher levels of team learning and interaction between VRI students, and 2) the significantly greater amount of welds performed by VRI students in the VR environment. In addition to fostering greater learning success, the use of VR integrated training greatly reduces training-associated costs.

Acknowledgments

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