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Use of Simulation to Improve the Effectiveness of Army Welding Training

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ABSTRACT

The use of simulation has the potential to provide safe, efficient and cost-effective welding training for the Australian Army and other training organisations. This report describes the outcomes of a DSTO study conducted to characterise key issues related to the use, design, and effectiveness of welding simulation. The study used a multi-method approach, including a literature review, discussions with staff and students at an Army trade training establishment, and a detailed analysis of the welding process. Results suggest that welding simulators can potentially provide effective training and save time and resources, when used in conjunction with traditional training. However, these findings appear to be restricted to novice welders due to limitations in how welding simulators assess performance and provide feedback. In addition, current calculations of the overall cost-effectiveness of welding simulation do not take into account factors such as staffing, infrastructure, and maintenance. The report discusses the implications of these findings for training and identifies areas for future research in this area.

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Use of Simulation to Improve the Effectiveness of Army Welding Training

Executive Summary

Welding is an important manufacturing technique used in a variety of industries, such as ship building, the automotive industry, and military engineering. The use of welding simulation has been proposed as a supplement to traditional, or live, welding training due to a number of perceived benefits including faster skill acquisition, cost savings and safety.

This report documents the outcomes of a study characterising the current state of knowledge relating to the use, design and effectiveness of welding simulation. The study was conducted by the Defence Science and Technology Organisation (DSTO) as part of a broader program of work investigating methods for enhancing the efficiency and effectiveness of the Army training system. Under this research program, DSTO was requested to provide support to the Australian Army in the acquisition and employment of welding simulation for trade training. The aims of the study were to address the following research questions:

1. What training benefits are provided by the use of welding simulation?
2. How should welding simulation be used in training? Specifically:
 - a. At what point in the learning cycle does simulation provide the most effective training?
 - b. What are the implications of using welding simulation for the role of the instructor?
 - c. What is the optimum ratio of live:simulated welding training?
3. What level of fidelity and feedback does the simulator need to deliver effective training ?

The study employed a multi-method approach involving a series of data collection and analytical activities to address these questions. This included a literature review into the design, use and effectiveness of welding simulators, discussions with staff and students at an Army trade training school and a detailed analysis of the welding process. The main findings are as follows:

- A combination of simulation and traditional methods can provide effective training for novice welders in basic weld types, as well as offering savings in time and resources, when compared to traditional training alone. However, the overall cost-effectiveness of welding simulation needs to account for all through life costs.

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- Simulation does not appear to be appropriate for training experienced welders or specialised welding skills, due to limitations in the way the simulator models welding performance.
- Simulation-based training is likely to be most effective where instructors are available to help interpret the augmented feedback provided by these simulators, as well as monitoring students' technique.
- There is insufficient data to determine the optimum ratio of live:simulated welding training beyond noting that effective training of basic welding tasks can be achieved using a significant proportion of simulation-based training (e.g., 50%).
- While simulators offer a range of feedback options, it is not clear which of these options are required for effective training. Effective training of some basic welding skills can be achieved without high levels of fidelity.

While these findings demonstrate a degree of utility for these devices, future research is required in order to achieve more efficient and effective use of this technology. This includes:

- Determining whether greater simulator fidelity will provide increased training benefit.
- Measuring the training effectiveness of simulators over a wider range of tasks and trainee experience levels, including specialist welding techniques and advanced welders.
- Determining the optimum training design for the delivery of simulation-based training.
- More comprehensive characterisation of live welding performance and hence more accurate performance modelling in simulators.
- Determining which aspects of feedback (i.e., sound, weld pool appearance) are the most important in achieving effective training outcomes and the extent to which this factor depends on welding experience.

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Contents

ACRONYMS

1. OVERVIEW.....	1
2. METHODOLOGY.....	2
2.1 Literature Review.....	2
2.2 Discussions with Welding Subject Matter Experts and Students.....	2
2.3 Observations of Simulator Training.....	3
2.4 Welding Task Analysis.....	3
3. WELDING OVERVIEW	3
3.1 Learning to weld	6
3.2 Welding in Army trade training.....	8
4. REVIEW OF DESIGN, USE, AND EFFECTIVENESS OF CURRENT WELDING SIMULATORS	8
4.1 Design of welding simulators	9
4.2 Performance assessment.....	11
4.3 Feedback.....	13
4.4 Training using Simulators	14
4.5 Evaluations of simulator effectiveness.....	15
4.5.1 User evaluation surveys	15
4.5.2 Transfer of training evaluations	17
4.6 Cost-effectiveness	21
5. DISCUSSION	23
5.1 What training benefits are provided by the use of welding simulation?	24
5.2 At what point in the learning cycle does simulation provide the most effective training?	24
5.3 What are the implications of using welding simulation for the role of the instructor?.....	26
5.4 What is the optimum ratio of live:simulated welding?.....	26
5.5 What level of fidelity and feedback does the simulator need to deliver effective training?	26
5.6 Future research on welding simulation.....	27
6. CONCLUSION	28
7. REFERENCES	29
APPENDIX A: TASK ANALYSIS.....	32
A.1. Gas Metal Arc Welding (aka Metal Inert Gas Welding) task analysis.....	33
A.2. Manual Metal Arc Welding (aka Stick Welding) Task Analysis.....	35

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Acronyms

AR	Augmented Reality
DSTO	Defence Science and Technology Organisation
FIC	Fundamental Input to Capability
GMAW	Gas Metal Arc Welding
HMD	Head Mounted Display
MMAW	Manual Metal Arc Welding
SME	Subject Matter Expert
TE	Training Establishment
UV	Ultraviolet
VR	Virtual Reality

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1. Overview

Welding is an important manufacturing technique used in a variety of industries, such as ship building [1, 2], the automotive industry [3], and military engineering [4, 5]. While advances in technology have allowed the automation of some welding processes, particularly in the automotive industry [6], there is still a strong demand for manual welding. Consequently, there is a need to ensure that welding training is safe, effective, and efficient.

The use of welding simulation has been proposed as a supplement to traditional, or live, welding training. Simulation is perceived to offer increased training benefits due to the ability to provide additional feedback that is not available during live welding [2, 7-9]. In addition to reducing the need for instructor intervention, this feedback is expected to lead to faster skill acquisition and hence save time when compared to live training [6]. Furthermore, as a simulator does not use real electrodes, plates, or other consumables, welding simulation is perceived to be cheaper than live welding [10-12]. Finally, simulated welding is considered safer than live welding, as there is no risk of radiation exposure, burns, or exposure to hazardous gases [6, 12, 13]. These drivers – increased training benefits, time and cost savings, and safety – are similar to the drivers for the use of simulation in many other areas such as aviation, medicine, driver training, and law enforcement [14-17].

This report documents the outcomes of a study into the use of simulation for welding training. The broad purpose of this study is to characterise the current state of knowledge relating to the use, design and effectiveness of welding simulation, in order to highlight issues for researchers, industry and training organisations working in this domain. In addition, the study findings are relevant to the broader use of simulation for training, particularly for fine motor skills similar to welding.

The study is part of a broader program of research within the Defence Science and Technology Organisation (DSTO) investigating methods for enhancing the efficiency and effectiveness of the Australian Army training system. Under this research program, DSTO was requested to provide support to Army in the acquisition and employment of welding simulation for trade training. Accordingly, the following series of research questions were developed by the authors, based on their previous experience in the field of simulation-based training [18-20]. These questions are applicable to simulation-based training in general, as well as addressing Army's specific support requirements, as discussed in Section 3.2.

1. What training benefits are provided by the use of welding simulation?
2. How should welding simulation be used in training? Specifically,
 - a. At what point in the learning cycle does simulation provide the most effective training?
 - b. What are the implications of using welding simulation for the role of the instructor?
 - c. What is the optimum ratio of live:simulated welding training?
3. What level of fidelity and feedback does the simulator need to deliver effective training?

The report begins with a description of the study methodology, followed by a short overview of the welding process (including an explanation of how welding training is typically conducted), and a brief description of welding as part of trade training in the Army. In the next section, the outcomes of a literature review into the design, use, and cost effectiveness of current welding simulators are presented. Significant findings are then discussed, relative to the study research questions; additional implications for the use of simulation for welding training are also highlighted. The report concludes with suggestions for future research and key lessons for the use of welding simulation.

2. Methodology

The study methodology was based on a series of data collection and analytical activities. These activities either directly addressed the research questions, or provided the contextual and supporting information required to address these questions. The activities are described in detail below.

2.1 Literature review

The aim of the literature review was to summarise the current state of research in the design, use and training effectiveness of welding simulation. Relevant references were obtained by using internet and database search engines to search for the terms “welding simulation”, “welding training”, and “cost effectiveness”. If relevant papers were located, further searches were conducted to identify any other papers that cited them.

All references found were then scanned for information relating to:

1. The design and function of welding simulators,
2. The method (actual or anticipated) by which the simulators were used in training,
3. The methodology and outcomes of any evaluations of the transfer of training from simulator to live environment, and
4. The methodology and outcomes of any evaluations of the cost-effectiveness of welding simulators.

2.2 Discussions with welding Subject Matter Experts and students

As part of the study, the lead author conducted several discussions with welding instructors (Subject Matter Experts - SMEs) and students at an Army training establishment (TE), as well as observing welding training. Discussions focussed on the following:

- The basic welding process,
- Welding training in Army, including the role of instructors and performance assessment,
- Differences in welding technique and the use of feedback between instructors and students, and
- Staff and student views on how simulation could be used in the training program. These personnel had some experience with older welding simulators used in the TE, which were in the process of being replaced.

This was supplemented by the literature review, as well as a review of technical documentation.

Observations of simulator training

In addition to discussions with staff and students, the lead author also observed simulator training provided to the welding instructors, as part of the introduction into service of new welding simulators at the Army TE. This provided the author with first-hand knowledge of the design and operation of a modern welding simulator, in particular, how welding performance is assessed and the type of feedback provided.

2.3 Welding task analysis

A detailed task analysis of the welding process was conducted for two key types of welding; this is described in Appendix A. This process was conducted in order to understand the welding process in greater detail, as well as identifying those tasks where simulation could be used to enhance the learning of critical welding skills through the provision of augmented feedback¹. The task analysis was conducted after several visits to the TE, discussions with instructors and students, and observation of live welding.

3. Welding overview

This section contains a brief overview of welding, in order to provide the reader with a basic understanding of some of the technical aspects of welding, including weld types and welding positions. While there are a number of different types of welding, this review concentrates on arc welding as this is the method used predominantly in Army trade training. In this process, an electric arc is created between an electrode, housed in a hand-held welding gun, and the surfaces to be welded. The heat generated by the arc melts the surfaces and electrode, creating a molten pool of metal, known as the weld pool. At the same time, a filler material is melted and added to the weld pool. As the welding gun is moved across the surface, and the heat reduces, the surfaces and filler material solidify, and bond together. This process can be repeated multiple times to build up the welded surface; the result of each individual pass is known as a 'weld bead'. Shielding gasses are dispensed during the welding process in order to maintain the integrity of the weld. An example of arc welding is shown in Figure 1.

Two subcategories of arc welding are Gas Metal Arc Welding (GMAW), and Manual Metal Arc Welding (MMAW). In GMAW, a wire (which is automatically fed through the welding gun) acts as both electrode and filler material. MMAW uses a consumable electrode which also provides the filler material. These two weld types are discussed in detail in this report as the TE was considering using simulation of these weld types to supplement traditional welding training.

¹ [46] defined augmented feedback as information provided to the human operator in a skill task which is supplementary to the feedback inherent in the operation of the task itself (i.e. intrinsic feedback). In addition, the distinguishing characteristics of augmented feedback are that it represents an evaluation of operator system performance and occurs with minimal lag.



Figure 1: A member of the Australian Department of Defence conducting arc welding (source: Department of Defence)

There are four parameters that define the welding technique and are considered to be critical in determining the quality of the weld. These are: arc length, travel speed, travel angle and work angle [1, 3, 7, 10, 21-25]².

- Arc length refers to the vertical distance between the electrode tip and the surface being welded (Figure 2).
- Travel speed refers to the speed at which the welding gun is moved across the surface being welded.
- Travel angle is the angle between the electrode and the vertical or y-axis (Figure 3).
- Work angle is the angle between the electrode and the z-axis, which lies in the plane of the surface being welded, orthogonal to the direction of travel (Figure 3);

² While the authors of the references cited above generally agree that these four parameters are critical to a successful weld, there is disagreement over what the tolerances for these parameters should be in order to achieve a successful weld. Authors generally refer to industry guidelines, standards, or handbooks as the source of their values, but there does not appear to be a consensus view.

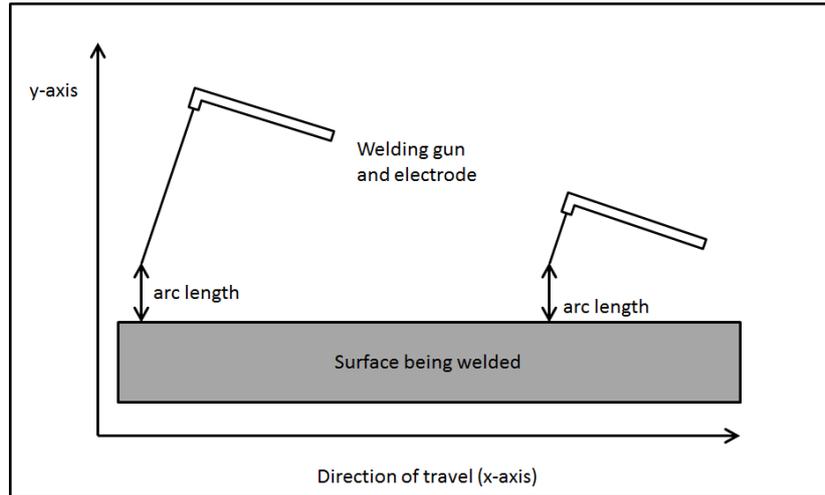


Figure 2: Arc length illustrated for MMAW. Note the adjustment to the height of the welding gun in order to maintain constant arc length.

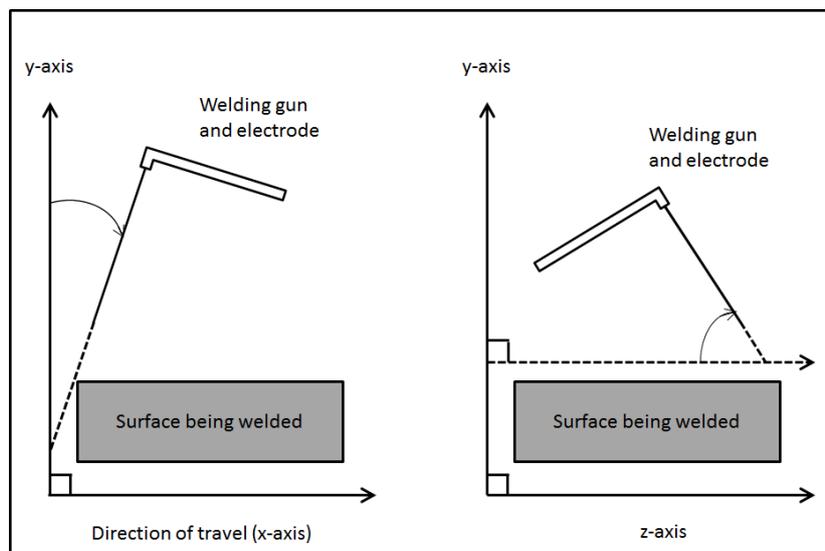


Figure 3: Travel angle (left) and work angle (right). In the right hand figure, the direction of travel (x-axis) is perpendicular to the plane of the page.

There are a number of standardised welding positions, identified by a letter and number combination. The number refers to the orientation of the weld; 1 indicates flat, 2 indicates horizontal, 3 indicates vertical, and 4 indicates overhead. The letter identifies the weld type; "F" refers to fillet welding, which is frequently used to join together perpendicular surfaces. In fillet welding, the weld pool forms a triangular shape at the point where the two surfaces join. The letter "G" refers to groove welding, where the weld pool fills the space between the surfaces. The combination of letter and number identifies the welding position, e.g. 1G is a flat groove weld, 3F is a vertical fillet weld, and so on [26].

Figure 4 illustrates a variety of welding positions. The white shapes are the welded surfaces, and the grey shapes represent the weld pool. Within each weld type, higher numbers indicate increasing difficulty. That is, within the different types of fillet welds, 4F is the most

complicated, while 1F is the easiest. It has been suggested that, overall, groove welds are more difficult to learn than fillet welds [25, 27].

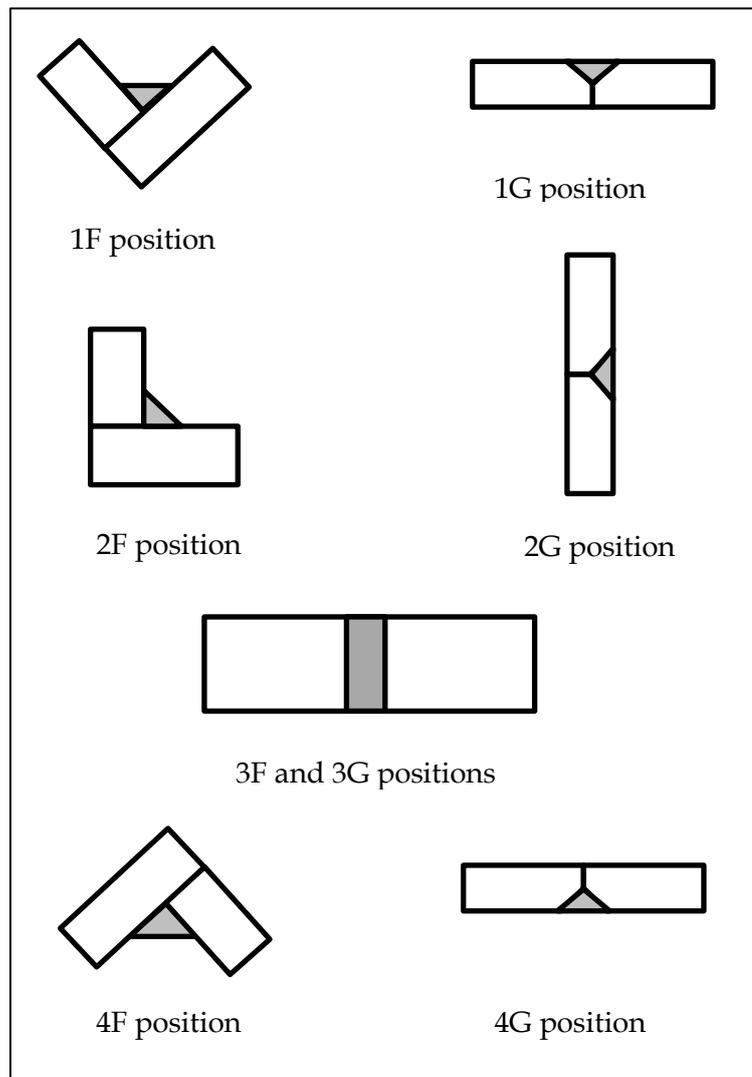


Figure 4: Welding positions. Note that from this perspective, it is impossible to differentiate between fillet and groove welds in the 3 (vertical weld) position, so one figure has been used to represent both weld types.

3.1 Learning to weld

Welding is a fine psychomotor skill. A competent welder must be able to make precise adjustments to travel angle, work angle, arc length, and travel speed, relying on the real-time feedback that is intrinsic to the welding process. This includes visual feedback from the appearance of the weld pool and the sparks produced, auditory feedback from the sound of the welding process, and haptic feedback from the feel of the welding gun. Changes to the critical parameters will result in immediate changes to this intrinsic feedback. However, obtaining and interpreting the feedback is made difficult by a number of factors. Firstly, welders are required to wear a variety of safety equipment such as a protective apron, gloves and face/eye protection such as UV filtering helmets [6]. This safety equipment tends

to limit the welder's movement. Haptic feedback is limited because the gloves reduce the welder's ability to feel the welding gun. The narrow aperture in the welding helmet reduces the field of view and UV filtering helmets reduce visual contrast, making it difficult to observe the details of the weld in progress. Since even small deviations from the correct technique can ruin a weld, the process of learning to weld takes considerable time.

An experienced welder is able to interpret the feedback, make assessments about the likely weld quality, and adjust their technique accordingly. However, this skill is difficult to learn, particularly in the very early stages of training. Furthermore, experienced welders (e.g., welding instructors) use a greater range of feedback than students. Students who were interviewed in this study indicated that they relied primarily on the characteristics of the weld pool to judge weld quality, and did not tend to use the sparks (sound and appearance). In contrast, instructors were more likely to use a broader range of feedback, including haptic and auditory.

Traditional (live) welding training is conducted broadly in line with the following key training principles [28, 29]:

1. Training must allow students to practise relevant skills,
2. Training must include performance assessment,
3. Students should be provided with feedback during and after training.

In traditional welding training, students repeatedly practise their welding skills under the supervision of a qualified instructor. The instructor may demonstrate correct welding technique, observe the student and provide real-time feedback on welding technique, or provide feedback based on the appearance of the finished weld [10, 25]. In addition, the weld quality can be assessed through mechanical or x-ray testing [2, 10]. Such testing typically provides feedback on the weld composition and physical characteristics such as strength and hardness.

While important, instructor feedback and performance assessment through mechanical or x-ray testing are of limited utility to novice welders. Instructor feedback is of limited utility because instructors can only provide feedback on the physical appearance of the weld, not its mechanical properties. In addition, if instructors wish to provide feedback while students are conducting welding, the requirement to wear safety equipment limits the observer's field of view to almost the same extent as the welder's. While mechanical testing and x-rays provide an accurate assessment of the weld quality, these tests take time to perform. Consequently, they are unable to provide the immediate feedback which is required for students to improve their technique during welding, until they have learned to utilise the intrinsic feedback described above.

Welding simulation is potentially able to address these limitations through the provision of immediate and augmented feedback to students on their welding technique. The task analysis conducted in Appendix A shows that the tasks which are the most critical to the welding process and which would benefit the most from augmented feedback are as follows:

- Holding the welding gun in the correct position,
- Moving the welding gun along the plate, observing and adjusting the position, speed and angle of the gun if required, and

- Observing the intrinsic feedback (i.e. characteristics of the weld pool, sparks and sound) and adjusting the position, speed and angle of the gun if required.

The tasks identified are those that welding SMEs indicated were the most difficult for students to learn, and do not include ancillary tasks such as assembling and preparing material and adjusting equipment. Consequently, it is anticipated that these factors would drive the design of welding simulators; this is explored further in Section 4.1.

3.2 Welding in Army trade training

In Army trade training, the specific welding tasks vary according to the types of metal used and the standard of welding required. Some of the most straightforward welds include working on a gate or a fence; this is relatively simple as it is conducted using standard metal, and the weld will not be required to support weight or carry a load. In contrast, specialist welding skills are required for more complex welds, such as repairing vehicle armour. These welds are more difficult due to the type of metal used, the requirement for a higher standard of weld to ensure the armour protects the crew, and the need to weld on curved and raised surfaces.

Discussions with SMEs indicated that there were no major issues with Army's current welding training program. However, the occasional requirement to increase throughput could cause difficulties due to limitations in the number of live welding systems and instructors. This issue was one of the main reasons for the acquisition of welding simulation and the driver for Research Questions 1 and 2b, in that Army was interested in whether the use of simulation could reduce instructor workload and hence improve throughput. In addition, instructors were seeking better ways for managing remedial training for novice welders who were struggling to develop their welding skills; this was the main driver behind Research Question 2a. The training of specialist welding skills was not a major consideration in the acquisition of simulation. However given that this forms an important part of Army trade training, there was interest in whether simulation had any utility in training these skills; this aspect is covered by Research Question 3a.

4. Review of design, use, and effectiveness of current welding simulators

The previous sections have identified that successful welding requires the welder to maintain the critical parameters within certain tolerances through interpreting the feedback intrinsic to the welding process. Welding simulation can potentially assist with the process of learning these skills by providing augmented or additional feedback. This section (based on a review of the literature) provides an overview of the types of welding simulators that have been developed, examines how they measure welding performance and provide feedback; explores how they could be used in training; and reviews the evidence for their cost-effectiveness.

4.1 Design of welding simulators

A number of different welding simulators have been developed by researchers, practitioners, and industry. Some of these are commercially available and widely used, such as the ARC+ and VRTEX systems; the latter is currently used by Army for trade training [7, 25, 30, 31]. In addition, a number of universities, technical colleges, and military training establishments have designed their own simulators for training and experimentation. These systems are not commercially or widely available [1, 10, 12, 21, 23, 32, 33]. Most of the simulators reviewed were designed to train MMAW [12, 21, 25, 30, 34, 35], GMAW, [1, 10, 11, 23, 24, 36] or both [6, 7].

The basic design of welding simulators is in accordance with the key training principles stated previously in Section 3.1; that is:

- Training must allow students to practise relevant skills,
- Training must include performance assessment,
- Students should be provided with feedback during and after training.

In order to satisfy the first principle, all welding simulators incorporate the basic components of live welding equipment, consisting of, as a minimum, (1) a welding gun and electrode and (2) a welding surface. Beyond this basic design, the welding simulators reviewed vary in complexity. The majority of simulators consisted of replica welding equipment, which has been instrumented with sensors to measure welding performance and provide feedback, [1, 8, 25]. In some cases the simulator consisted of instrumented live welding equipment; this includes the simulators described in [21] and [32].

Two early examples of welding simulators from 1968 and 1974 are described in [37] and [10]. In [37], there is a description of a 1968 simulator where the student moved a replica gun and electrode along a fixed path, keeping time with a moving pointer. Points were awarded for keeping the electrode in contact with the gun, and deducted for allowing the gun to come in contact with the simulated welding surface. In [10], the simulator consisted of a replica welding apparatus equipped with sensors to track welding performance and some fairly simple devices, such as a light, to provide augmented visual, auditory, and haptic feedback.

Most modern simulators are run by a personal computer and employ software which enables a variety of processes. These include setting up (i.e. selection of materials, weld type and weld settings), performance assessment, and provision of feedback, in line with the second and third training principles. Typically, most modern simulators also employ Virtual Reality (VR) or Augmented Reality (AR) technology to provide the simulator display and visual feedback. In VR systems, a Head Mounted Display (HMD) is used to show the virtual environment. The welder cannot see the actual gun and welding surfaces; instead, they see a virtual representation of these projected onto the HMD [3, 7, 8]. Other simulators were Augmented Reality (AR) systems [2, 36]. Unlike the VR systems, in the AR systems, the welder can see the gun and welding surfaces they are interacting with. In both VR and AR systems, virtual imagery is used to provide visual feedback; this is described in more detail in Section 4.3. A separate monitor is also generally included to allow instructors to view student performance and review feedback after welding completion.

The simulator currently in use within Army is shown in Figure 5. The left-hand image shows the welding helmet. The inverted T shape on the clamp in front of the helmet is one of the surfaces used for simulated welding. The right-hand image shows the control station where the student or instructor selects the settings for the simulated weld. During simulated welding, the monitor can show either the student's view of the welding process, or information showing the student's performance against the critical parameters. This image also shows the welding gun, stored on the left-hand side of the control station. Figure 6 shows the welding simulator in use.



Figure 5: The welding simulator used by Army for trade training (source: Susannah J. Whitney)



Figure 6: The welding simulator in use (source: Susannah J. Whitney)

4.2 Performance assessment

The majority of simulators reviewed in the preceding section determine welding performance by measuring the critical parameters during the welding process. Typically, as a simulated weld is conducted, the values for the critical parameters are measured using sensors; for example an accelerometer can be used to measure work and travel angles. A model is then used to predict the quality of the weld. Sensor and model outputs are also used to provide visual, auditory, and haptic feedback during and after the welding process [2, 3, 6-8, 10, 11, 21-23, 32, 38, 39]; this is discussed further in Section 4.3.

Given that the weld quality is an essential element of the feedback provided to students, it is clear that the effectiveness of the simulator will depend on the accuracy of the model used to predict the relationship between live weld quality and critical parameter values. In some cases, critical parameter values are compared with published standards or industry guidelines and the resultant quality of the weld is assessed based on the degree to which welding performance lies within certain tolerances, e.g., [10, 23]. However these standards appear to consist of a range of critical parameter values that are representative of typical welding procedures. While this may be adequate for predicting gross errors, it may not be sufficient for accurate prediction of simulator weld quality, particularly if there are strong interdependencies between the parameters. Consequently, researchers have either used empirical data or mathematical modelling, as described below.

In [38], the authors collected empirical data from several hundred weld bead cross sections. They measured the characteristics of the weld bead, and hence weld quality, for a range of values of arc length, travel speed, travel and work angles, current, voltage and material type using an automated instrumented welding device. Neural networks were then developed in order to predict the weld bead characteristics from welding parameters. This model was then implemented into a virtual welding simulator equipped with sensors to measure critical parameters and various displays for showing welding performance and providing other feedback. A similar approach was adopted by researchers in [11] and [22]. In [22], the authors stated that, following testing and training of the neural network, they believed it

could be successfully used to assess welding performance. However, during an initial evaluation of the simulator, welding instructors found it difficult to execute good welds, which may indicate some limitations in the way the model determines weld quality.

In [21], the performance of expert and intermediate welders³ was measured using live welding equipment instrumented with electronic sensors. The authors measured these welders' performance on four key parameters, arc length, work angle, travel angle, and welding speed. They then compared the welders' performance to recommended guidelines for work angle and travel angle⁴. Interestingly, the results showed that while both groups were considerably outside the industry guidelines, the deviation was actually greater for the experts than the intermediate welders. For instance, the guidelines suggested that the work angle should be 45°. However, experts used an average work angle of 54°, and intermediate welders used an average work angle of 47°. In addition, the difference between expert and intermediate welders was statistically significant for all four key parameters⁵. The overall weld quality was not assessed.

These outcomes highlight two issues. Firstly, they reinforce the point that industry guidelines or standards may have limited utility for predicting weld quality, given that the skilled welders could execute successful welds even when operating outside of these standards. Secondly, the difference in parameters between intermediate and skilled workers suggests a relationship between welding experience and technique. This outcome may also have implications for how the relationship between parameter values and weld quality is predicted in simulators. For example, the empirical data collected in [11], [38] and [22] used automated welding methods, which may not reflect the welding techniques of all operators. This is discussed further in Section 5.2.

In [8], the authors used mathematical modelling to predict weld quality. The authors note that this method necessitates a trade-off between accuracy and processing speed; the computation times for detailed models are too long to provide real-time feedback. In [11], the authors propose the use of neural networks trained by both empirical data and numerical modelling to a more realistic representation of the weld pool. The commercially available VRTEX system is described as employing an "advanced physics engine", but no further details are provided [25].

One final issue that does not appear to be discussed in any detail in the papers reviewed is the accuracy of the sensors used to measure the critical parameters. If the quality of a live weld is highly sensitive to minor changes in the critical parameters, it is important that these values are measured with sufficient accuracy by the simulator sensors. However, the impact of sensor accuracy on model accuracy is not mentioned except in [8]. In this case the authors claim to achieve sub-mm accuracy in tracking the position of the welding gun, which they deem sufficient for the simulator to be useful for welding training. However, they do not provide any evidence to support this statement.

³ The authors report that the six expert welders were gold medallists from the Welding Olympics, while the six intermediate welders all had more than three years welding experience.

⁴ The source of these guidelines is not specified. In addition, the authors state that only work angle and travel angle have recommended tolerances; this is inconsistent with the views of other authors.

⁵ This analysis does not appear to take into account any uncertainties in the sensor measurements.

4.3 Feedback

When conducting live welding, feedback is mainly provided by the visual characteristics of the weld pool, the welding sound, and the haptic sensation of the contact between the welding gun and the welding plate. These are replicated to varying degrees of fidelity in most of the simulators covered in the literature review. In addition, these simulators can provide augmented feedback in the form of onscreen guides [6, 31, 32, 39], voice prompts [21] or other forms of audio feedback additional to the normal sounds of the welding process, such as voice prompts or tones [10]. This feedback can be provided during the welding process, after the weld has been completed, or both. This section discusses the way in which feedback has been incorporated into existing welding simulators. The subsequent training implications are discussed in Section 5.1.

The majority of simulators used VR or AR technology to provide a high fidelity visual representation of the weld pool. As described in Section 4.2, this was based on sensor measurement of the critical parameters during the welding process, in conjunction with mathematical modelling [8] or neural networks⁶ [1, 3, 11, 24, 36, 38]. It is not known how well the behaviour of the weld pool in the simulator needs to replicate that in live welding. However, any significant differences, such as time lag, could potentially reduce the training effectiveness of the simulator.

Onscreen guides are a form of augmented feedback common to most simulators. Typically, these consist of graphs or gauges showing values of the critical parameters over the course of the weld relative to desired values and are designed to show students the aspects of their technique requiring improvement [6, 11, 38]. These can be viewed in real-time, but are generally designed to be used immediately after the weld has been completed.

Another important source of feedback is the sound of the welding process. Several simulators [8, 11, 35] provided auditory feedback through recordings of the live welding process. This feedback tended to be binary; it was presented while welding was within set tolerances, but changed abruptly or ceased immediately these values were exceeded. There was no gradual change in the feedback to alert students that they were about to exceed the tolerances [8, 21].

Some simulators used augmented auditory feedback. This included tones and buzzing sounds [10] or spoken instructions such as 'Faster', 'Press Down', and 'Upward' [21]. This feedback was also binary. While this could inform students when they had exceeded the tolerances for critical parameters, the training value of this auditory feedback is unclear, particularly given the concerns surrounding how these tolerances were calculated (see Section 4.2).

Several simulators also used haptic feedback. For instance, in [35], the welding gun contained an electromagnet. If the gun and electrode were held too close to the surface being

⁶ In [8], the real-time appearance of the (molten) weld pool was calculated using mathematical modelling. The neural network calculations were based on the characteristics of the (solid) weld bead attained at the end of live welding; it is assumed that this data was also used to determine the appearance of the weld pool although this is not made explicit in these papers.

welded, magnetic attraction would bring them into contact, simulating the electrode adhering to the surface. In [38], the simulator's welding gun contained small vibrating devices. This was intended to replicate the vibration experienced by welders under 'inappropriate welding conditions'. While the authors state that this provided realistic haptic feedback, the fidelity level is unclear. In particular, it is not evident if the level of vibration increased with the inappropriateness of the welding conditions, or if the same level of vibration was used for all deviations from the standard (i.e. binary feedback). In addition, the authors do not explain the how 'inappropriate' welding conditions were determined, although it could possibly be inferred that this based on the neural network method used to assess weld quality in this simulator.

4.4 Training using simulators

The ability of simulators to capture, display, monitor and analyse feedback data has implications for the design and delivery of simulation-based training, when compared with traditional training. This includes how and when the feedback is used, and potential changes in the roles of instructors.

From the preceding discussion, it is clear that welding simulators provide a wide range of feedback, including augmented feedback as well as simulating the intrinsic feedback characterising live welding. It is less clear which types of feedback are necessary to produce improved welding performance, or the required level of fidelity. Overall, simulator designers appear to have attempted to maximise the amount and realism of feedback, within the constraints of cost and computing speed, without necessarily identifying how these factors contribute to training outcomes.

The experience level of the welder is expected to be an additional factor in determining the feedback requirements, as discussed previously. Novice welders, who rely on a narrow range of feedback in live welding, may be expected to benefit more from the augmented feedback provided by simulators, compared with more experienced welders. However, it is also possible for students to become overly reliant on feedback in the simulator that is not present in live welding (the so-called crutch effect [40]). Consequently, there may need to be a gradual reduction in the use of augmented feedback as training progresses, if the simulator continues to be used. This is consistent with the Dreyfus model of psychomotor skill acquisition, which characterises the different types of feedback required by learners [41].

The Dreyfus model contains five stages through which students progress as they learn. At the earliest stage (Novice), the emphasis is on learning the correct rules; in welding this could correspond to novice welders initially being reliant on automated feedback to inform them when they exceeded tolerances for the critical parameters. At level 4 (Expert), students use past experience; consequently, they are unlikely to require (or benefit from) augmented feedback, but would rely on the fidelity of (simulated) intrinsic visual, audio and haptic feedback. However, none of the studies reviewed appear to have explored these differences. Unfortunately, only one study examined the way novice welders use feedback during welding training [31]. This study will be discussed in more detail in Section 4.5, which examines the effectiveness of simulation-based welding training.

While it has been suggested that the provision of augmented feedback can reduce the need for instructor intervention [1, 8], it is still clear that instructors will continue to play an important role in simulation-based training for welding. Several of the simulators reviewed are designed to allow instructors to monitor and review student progress. For example, in [11, 24] a remote monitor is used to provide the instructor with a multi-view display of the virtual environment and tabular values of the welding parameters. The VRTEX simulator also includes an 'instructor CAM', which allows a second student or instructor to view the virtual weld in progress (see the right-hand image in Figure 5). However, while these features may seem impressive, the actual training benefit they afford is not known. In addition, it is not clear if instructors will require additional training in order to interpret the simulator's feedback and translate this into practical guidance for students.

In [1], it is suggested that the feedback data collected by the simulator can be used by the instructor to tailor a training program for each individual, by identifying the strengths and weaknesses in their technique. Rather than reducing the time instructors need to spend on training, this actually represents an additional training burden, although this may be a worthwhile investment if it leads to better training outcomes. In addition, it may take time for instructors to learn to interpret and implement the feedback provided by the simulator. Overall, the majority of papers reviewed do not provide any guidance of how to best incorporate welding simulation into a training curriculum. However, the manufacturer of the VRTEX simulator provides a series of lessons which it claims are designed to incorporate a blended learning approach combining live and virtual welding training [42]. They claim this approach has been proven to provide more effective and efficient training outcomes, but provide no evidence for this claim.

4.5 Evaluations of simulator effectiveness

While the majority of published papers on welding simulation tended to focus on the simulation technology, they also included some evaluation of the training effectiveness of the simulation. Two broad evaluation methods were used. The first was survey-based studies, where users completed evaluations after using a welding simulator [1, 11, 12, 22, 24, 36, 38]. The second category comprised studies where live welding performance was measured following simulation-based training [7, 10, 21, 25, 30, 31, 34]; that is, the degree of transfer of training from the simulator to the live welding environment..

4.5.1 User evaluation surveys

User evaluation surveys have generally asked participants to spend time interacting with the simulation, then rate elements such as fidelity, realism, and training effectiveness. For instance, the results of evaluations of a naval GMAW VR simulator are described in several papers [1, 11, 22, 24, 36]. In one evaluation, 104 people completed a survey after using the simulator. These people ranged from those with no prior welding experience to those with more than 20 years' experience. Results indicated that respondents were generally positive towards the welding simulator, reporting that they liked using it [1], that it was realistic [36], and they believed it to be a useful training tool [11, 24, 36]. Some issues with fidelity were identified, e.g. the brightness of the display and audio feedback. The authors do not provide some key methodological details, such as the amount of time each participant spent interacting with the simulation (although they do note that all 104 people used the simulator

over a 3 week period, suggesting the interaction time was limited), or the extent to which interaction with the simulator was structured or standardised across participants.

In another study, the same naval GMAW VR simulator was evaluated by welding students and instructors [22]. Participants rated the simulator on a number of dimensions on a five point scale, where one was the lowest rating, and five the highest. While results are not presented in detail, the average score for the dimension 'useful for learning to weld' was 1.25, suggesting that participants did not see a great deal of training value in the simulator. Free response comments identified that the simulator lacked realism. The authors do not report whether this referred to specific aspects of the simulator or the simulator as a whole. In addition, the authors downplay the criticisms of lacking realism, suggesting that participants only disliked the graphics because they did not compare to video games.

In addition, [22] reports that when the welding instructors were interviewed, many reported that they found it very difficult to execute welds that the simulator rated acceptable. This occurred even when the instructors paid close attention to their technique. This suggests that the simulator's tolerance settings for the critical parameters was too narrow, which may be a result of limitations in how the relationship between weld quality and critical parameter values is determined, as noted previously in Section 4.2.

Evaluation of another welding simulator is described in [12]. In this study, 136 students at a technical college completed a questionnaire examining their views on the training effectiveness of a VR simulator. The authors reported that the participants believed that simulation was effective for training a variety of aspects of welding, including current adjustment, work piece preparation, the 1G welding process, electrode touch distance, electrode movement speed, movement and working angle determination. However, they rated live welding as more effective than virtual welding. Some limitations of this study are that there was no direct examination of welding performance, and the methodology and results are not discussed in detail.

A similar evaluation was conducted in [38]. Participants in this study were six novice welders enrolled in a welding training course in a technical college. After two days of classroom learning and training with real welding equipment, participants spent time using a VR simulator. Following this, they completed a survey rating the realism of various aspects of the virtual environment, and the usefulness of the simulation. Results, although not presented in detail, indicate that the realism of the simulator was not highly rated. However, participants found some aspects of the simulator useful, including the feedback provided during and after the welding process.

These studies generally indicate that participants have a positive attitude towards the use of welding simulators for training. However, the limited information provided by the authors of these studies regarding the methodology and results makes it difficult to assess the rigour with which the studies were conducted, and the strength that can be placed on their findings. For instance, none of these papers provide detailed information on the length of time people spent using the simulator prior to evaluation, the range of activities they conducted, and whether or not any feedback or instruction was provided.

In addition, user attitudes alone are not sufficient to demonstrate that welding simulators provide effective training. While positive attitudes may be an important factor when engaging in and committing to simulation-based training, as noted in [18, 43], attitudinal measures should not be used as the sole measure of effectiveness. A more robust evaluation is provided by measurement of the extent to which live welding performance improves following simulation-based training.

4.5.2 Transfer of training evaluations

This evaluation method forms the second category of studies reviewed. While in principle, this evaluation method is considered to be scientifically more rigorous, the quality of studies in this category varies. For instance, [7] reports that a novice was able to reach an acceptable standard of welding following eight hours of simulation-based training and four hours of live training, and that another novice was able to successfully complete traditional live welding training following use of the VR simulator. These are the only results the author includes to demonstrate the training effectiveness of the simulator and are of little or no value in assessing the actual contribution of the simulator to training outcomes. For instance, it is possible that the novice who achieved competency following eight hours of simulation-based training and four hours of live training could have reached competency after a shorter period of live training.

In [34], four novice welders completed a series of three live welds to measure their baseline performance. The participants then completed a series of ten simulation-based welds using a VR welding system. At the end of each simulation-based weld, two of the participants received feedback showing how their performance compared to pre-defined values for the critical parameters, while the remaining two participants received no feedback. Following simulation-based training, all participants completed another series of three live welds. Results suggest that participants who received feedback performed better on the second series of live welds than those who did not. However, the authors only provide limited detail on results. They do not report any statistical testing, or the magnitude of performance difference between participants who did and did not receive feedback. The authors also claim that following training, participants' performance resembled that of skilled welders. Given the extremely limited training time, this claim appears ambitious, and the authors do not provide any additional data in support of this claim.

In [21], the effect of feedback on welding performance was examined. Participants were 60 novice welders enrolled in a university engineering course. They were randomly allocated to the feedback or no feedback conditions. Participants were required to perform four sets of welding, during which the values for the critical parameters for arc length, work angle, travel angle and welding speed were measured using sensors. In the feedback condition, whenever participants' performance on the simulator went outside standard values of the critical parameters⁷, the simulator provided immediate auditory feedback such as 'Faster', 'Press Down', and 'Upward'. Participants in the no feedback condition did not receive this feedback. Participants' performance against these standard critical parameter

⁷ These standard settings were based on the average of industry guidelines and the performance of intermediate standard welders, determined earlier in the study.

settings was measured for analysis. The quality of the final set of welds was assessed by experts using a 5-point scale.

Results from the live welding assessment indicated that the mean score of the feedback group was significantly higher than the score of the no feedback group⁸. In addition, the two groups differed significantly on arc length, travel angle, and welding speed. The feedback group was closer to the standard settings for travel angle, although the no feedback group was closer to these settings for arc length. Welding speed was faster for the feedback group than the no feedback group. Welding speed was closer to the experts' speed for the feedback group, although the no feedback group was closer to the standard values for welding speed implemented in the simulator.

This study does not directly measure the effectiveness of simulation-based training relative to conventional live training. However, it did demonstrate that the provision of feedback results in significantly better live performance than the absence of feedback. Surprisingly, the no feedback group was closer to the standard settings, despite the fact that the overall quality of their live welding was poorer than participants in the feedback group. This suggests that, as we have discussed elsewhere, standard or industry settings for critical parameters in welding do not appear to characterise welding performance with sufficient accuracy.

A more rigorous evaluation of a welding simulator is described in [10]. Rather than using VR technology, this simulator used a physical replica of the welding gun and welding plate, with visual, haptic, and auditory feedback provided when tolerances for the critical parameter settings were exceeded. This study is almost 40 years old and the simulator quite rudimentary compared with the majority of simulators described in this review.

Participants in this study were 36 novice welders enrolled in a naval technical training course. They completed a pre-training welding assessment, which was used to allocate them into either the experimental or control group using a matched pairs method. All participants then completed a standardised training program, working at their own pace. Participants in the control group spent this time solely conducting live welding, while participants in the experimental group spent 50% of their time conducting simulated welding, and 50% conducting live welding. Following training, all participants completed a final live weld, which was assessed by assessors who were blind to the training method. Results showed that mean scores on the final live weld were significantly higher for the experimental group than for the control group. The authors note that while both groups spent comparable amounts of time training, the control group spent the bulk of its training time on ancillary behaviours such as adjusting equipment or changing the rod, while the experimental group spent the bulk of its time conducting welds (live and simulated). The authors concluded that the welding simulator provided effective training, with fewer resources used than live training [10].

Two evaluations of a modern welding simulator are described in [25, 30, 31]. These are the most comprehensive and methodologically rigorous evaluations of those studies reviewed.

⁸ No-feedback in this case means no augmented auditory feedback; trainees still received the usual intrinsic feedback provided by the welding process.

The first study, reported in [25, 30] compared the effectiveness of a commercially available VR welding simulator, the VRTEX 360, with traditional welding training. In this study, 22 welders were randomly assigned to either a control group or an experimental group. The majority of participants had no previous welding experience. Four participants who had some welding experience were evenly distributed between the experimental and control groups. The control group received traditional training, comprising lectures and hands-on welding practice. The experimental group received 50% traditional and 50% VR training.

Over a two week period, participants were trained by a qualified welding instructor on four welding positions; 2F, 3F, 1G, and 3G (see Figure 4, page 6). This sequence represented a progressive increase in the difficulty of the weld [25, 27]⁹.

All participants were allowed a maximum of 80 hours training time. At the end of this time, or earlier if the instructor deemed it appropriate, participants completed live welds in each of the four positions. The completed welds were then independently assessed. Two additional types of measurement were used to examine differences between the experimental conditions. First, during training, participants' muscular activity was measured via electrodes attached to their skin. Second, at the conclusion of training, all participants completed questionnaires measuring their cognitive development in the areas of knowledge, comprehension, application, and analysis.

Results from the welding assessment indicated that, across the four welding positions, competency was achieved for a higher number of students in the experimental group than in the control group. This difference was not statistically significant for any comparison. While the majority of participants achieved competency in the easiest weld, 2F (11 from the experimental group, nine from the control group), as the weld difficulty increased, the number of participants achieving competency decreased. Only nine participants (five from the experimental group, four from the control group) achieved competency in the most difficult weld, 3G. When the certification scores were analysed, the experimental group recorded higher scores than the control group for three weld types, with a statistically significant difference for the 1G weld. The control group outperformed the experimental group by one percentage point on the 3G weld, but this difference was not statistically significant [25, 30].

When the amount of time each group spent training was compared, results indicated that the experimental group spent significantly less time training than the control group, for each of the four welds. The experimental group spent approximately 12 hours training on each weld type, compared to between 14 and 15 hours for the control group. This difference was statistically significant for all comparisons [25, 30]. It is not clear from the articles if this difference in time spent training results from the experimental group learning more quickly, or the experimental group having to spend less time in ancillary tasks such as setting up the welding equipment.

⁹ As discussed previously, in general groove welds are considered more difficult than fillet welds, and higher numbers indicate higher levels of difficulty. The order in which welding positions were taught in this study implies that all fillet welds are easier than all groove welds, although it is not clear if this is accepted industry-wide.

This study also measured the consumption of real and simulated resources, and the cost-benefit implications, in each condition. The results showed that resource usage and cost was less for participants in the experimental group [30]. This will be discussed in more detail in Section 4.6.

A follow up study conducted by the same researchers is described in [31]. In this study, 21 novice welders were assigned to a group receiving either 100% virtual welding training, or a mixture of 50% virtual and 50% live welding training. The methodology was similar to the previous study; the same four welding positions were used, participants completed a live weld following training, and cognitive development and muscular activity were measured. In this study, the duration of training is not specified, hence there was no analysis of time taken to achieve competency. In addition, feedback on arc length, work angle, travel angle, and travel speed was provided through on-screen illustrations, where coloured pointers and targets indicated the correct orientation and movement. Participants could select the amount of feedback they wished to use, by choosing one of eight overlays, each containing a different combination of parameters:

1. No feedback
2. Arc length
3. Work angle and travel angle
4. Travel speed
5. Arc length, work angle, and travel angle
6. Arc length and travel speed
7. Work-travel angle and travel speed
8. Arc length, travel speed, work angle, and travel angle

Results indicated that the only significant difference in qualification levels occurred for the 3G weld, where a significantly higher percentage of participants qualified in the 50% VR group (approximately 45% qualified) compared to the 100% VR group (10% qualified). There were no significant differences in muscular activity between conditions for any of the welding positions, but participants in the 50% VR group recorded significantly higher knowledge analysis scores than the 100% VR group for the 3G welding position. From these results, the authors [31] concluded that live and virtual welding training were equally effective for all bar the 3G welding position. However, they acknowledge that it may have been unrealistic to expect participants to master the complex 3G position in the limited training time available.

Results also indicated that welds where feedback overlays 4 and 5 were used had the highest mean quality scores. Further analysis showed that overlay 5 was more frequently used and resulted in higher pass rates than the other overlays. From this, the authors concluded that this overlay represented the most widely used and effective training strategy. However, these conclusions need to be tempered by the small sample sizes involved, and the fact that participants could chose the overlay. For example, only one participant selected overlay 2 and no-one selected overlay 7.

The outcomes presented in this section provide some evidence that a mixture of live and simulated training is more effective than live training alone¹⁰. This is based on a number of measures including superior welding performance [10, 25, 30], significantly better knowledge of welding [25, 30], and shorter training time [25, 30]. The evaluations also suggest that simulation-based welding allows students to spend less time on ancillary tasks such as assembling and preparing material, and more time practising core welding skills such as moving the welding gun and interpreting feedback from the welding pool [10], although the time savings are not described in detail. As identified by the SMEs, and supported by the task analysis (Appendices A and B), these skills are more difficult and take longer to learn than the ancillary tasks, hence allowing students to focus on these skills may result in faster improvement.

There is also a suggestion that simulation can have negative training effects. For example in [25], it was noted some participants were observed using a can or grinder to support their elbow while they welded using the simulator. While this may be useful in the short term in providing stability and preventing fatigue¹¹, it is undesirable in the long term due to the development of inappropriate techniques. However, this is not an inherent flaw of the simulation, but instead, highlights the importance of supervision of training (live and simulated) to ensure students are developing appropriate techniques.

4.6 Cost-effectiveness

The cost-effectiveness of training can be defined as the cost required to achieve particular training outcomes; measures include reduced use of materials or personnel, reduced training time, or increased productivity [44]. In this section, the evidence for the cost-effectiveness of welding simulation is presented. This includes any evidence for where time or resources have been saved through the use of welding simulation, as well as an examination of additional factors that may have an impact on cost-effectiveness calculations.

Authors have identified a number of areas where time, money, or both, can be saved as a result of the use of welding simulation for training [2, 6, 10, 24, 30, 38]. For example, in [10], the authors calculated that their welding simulator used 215 times less power than the live welding system. In this study the experimental group conducted 50% live and 50% simulator training; on this basis, the authors calculated that the experimental group consumed 33% less energy than the control group during training. Given that the experimental group achieved superior training outcomes to the control group, these outcomes provide evidence for the cost-effectiveness of 50% live / 50% simulator training, (relative to all live training). However, this research was published in 1974, consequently it is not known whether modern welding simulators would result in comparable electricity savings.

¹⁰ The findings from [31] also suggest that a mixture of live and simulated training is more effective than 100% simulated training. While interesting, this finding may be of limited practical utility because there appears to be no suggestion in any of the papers reviewed that live welding training should be wholly replaced with simulation-based training. Rather, the consensus view appears to be that simulation should be used as a supplement to live training.

¹¹ Participants in this condition required significantly shorter training time than participants completing a mixture of live and simulated welding. Hence, the use of simulation is unlikely to have caused fatigue above and beyond that experienced by participants completing live welding only.

Data on time and resource savings are also presented in [30]. As discussed in Section 4.5.2, this study compared the performance of novice welders receiving a 50:50 mix of traditional and simulated training (the experimental group) with the performance of novice welders who received only traditional training (the control group). Results indicated that the experimental group achieved competency significantly faster, e.g. 12.27 hours vs. 15.05 hours for the 2F position. In addition, this group recorded significantly higher assessment scores on the 1G welding positions than the control group. The authors also calculated that the per-student cost of plates and electrodes was \$137.60 for participants in the experimental group, and \$190.97 for participants in the control group. Hence, in this study, the use of simulation appeared to result in faster time to qualify and resource savings of approximately \$53 per student (28% cheaper), whilst achieving a similar (or better) standard of welding. Taken together, these outcomes provide some evidence for the cost-effectiveness of this specific combination (50:50) of simulation-based and live training.

There are numerous other claims regarding the cost-effectiveness of simulator training; however the lack of detail provided means that they cannot be considered as reliable evidence. For example, in [1] the authors make the following claims about the time and resource savings associated with simulation for the US Naval and shipbuilding industry:

- The use of welding simulation could save USD\$2.5 million annually,
- A 2% improvement in GMAW productivity would result in cost savings of USD\$325,000 per submarine hull,
- Savings of 50% could be achieved by “providing 100% feedback to trainees & reducing and targeting instructor contact time”, and
- Simulation produces a 4:1 return on investment.

The projected cost savings of \$2.5 million may seem impressive, but without a more detailed breakdown of all costs involved it is difficult to assess the significance of this saving. Likewise, ‘GMAW productivity’ is not clearly defined, nor is the basis of the claim for simulation producing a 4:1 return on investment explained in any detail.

In summary, the papers reviewed in this section have provided some evidence for the cost-effectiveness of welding simulation, based on the relative cost of consumables and training times for simulation and live welding. However, this only represents one of many costs associated with training; a more comprehensive, systematic approach which considers a broader range of factors is likely be required when making decisions regarding the acquisition and employment of welding simulation [23].

A Fundamental Inputs to Capability (FIC) analysis is one possible method for identifying the source of these costs. FIC comprises eight categories, which need to be considered in the acquisition of a capability:

- Personnel
- Organisation
- Collective Training
- Major systems
- Supplies
- Facilities and Training areas
- Support

- Command and Management

It is beyond the scope of report to conduct a FIC analysis in detail; however, it is apparent that several of these categories will be relevant to the use of welding simulation. Some examples are included in Table 1 below.

The example of instructor and student training under the Personnel category was previously discussed in Section 4.4. As a welding simulator represents a new capability, and as there are several features that are not present in live welding equipment, the introduction of simulation has training implications for both instructors and students. This includes learning procedural aspects such as start-up and shut-down and other aspects such as learning how to interpret and make best use of augmented feedback. This training represents an additional cost and time overhead, but failure to learn these skills may have a detrimental impact on training outcomes.

The main implication is that for any organisation looking to introduce welding simulators in their training program, there are a number of up-front and ongoing costs that need to be considered. Over the life of the simulator, these costs may well be significant compared with any savings achieved where the initial acquisition cost of the simulator and resource consumption is less than that for the live system.

Table 1: Examples of Fundamental Input to Capability costs associated with the acquisition of welding simulation

FIC	Example costs
Personnel	Training for instructors and students in the effective use of the simulator Additional instructors, where the acquisition of simulators leads to an increase in throughput
Organisation	Changes to the training program in order to incorporate simulation-based training
Supplies	Power consumption
Facilities and Training	New facilities or modification/extension of old facilities to house new simulators
Support	Maintenance contract for simulators, including technical support and upgrades
Command and Management	Appropriate leadership and change management processes may be required to ensure acceptance of new technologies such as simulation

5. Discussion

The previous sections have highlighted the key findings relating to the use, design and effectiveness of welding simulation. In the following sections, we discuss these findings in the context of the three specific research questions. Implications for the use of simulation for welding training are also highlighted.

5.1 What training benefits are provided by the use of welding simulation?

The first finding from this study is that welding simulation is able to provide effective training, based on the three studies [10, 25, 30, 31], which examined transfer of training from the simulator to the live environment (Section 4.5.2). All of these studies found that a mixture of simulation-based training produced equivalent or better training outcomes than live training alone (or simulation-based training alone). However, these studies were limited to novice welders and a small number of weld types. Additional studies will be required to examine a broader range of welding conditions and welding experience in order to provide a more comprehensive evaluation of the utility of welding simulation.

This study also identified a number of welding simulation evaluations based on questionnaires, surveys, or ad-hoc evaluations (Section 4.5.1). While these methods are not as robust as transfer of training studies, these findings also provide some evidence that welding simulation can provide effective training.

This report has found no evidence of negative training in terms of the welding skills learned using the simulator. However, as noted in Section 4.5.2, a lack of supervision resulted in novice welders using a support for their elbow; this has the potential to lead to negative training in the long term, although it is not directly associated with the simulator.

The overall cost-benefit of using simulation compared with live training is hard to quantify accurately. This report has identified some cases where use of simulation resulted in savings in time and resources (Section 4.6). However, additional costs such as those associated with staff, infrastructure, and facilities also need to be considered. This does not imply that use of simulation cannot provide cost-effective training, but organisations considering acquiring this capability should include these factors in their planning. A formal FIC analysis may assist this process.

While the majority of studies discussed in this report used high-fidelity simulators, it is noteworthy that transfer of training was also found in a lower-fidelity simulator [10]. This suggests that a high degree of fidelity is not necessarily required for effective training. Lower fidelity, and lower cost options, may be as effective and hence provide greater cost-effectiveness than high fidelity, high cost options.

5.2 At what point in the learning cycle does simulation provide the most effective training?

In terms of student experience, the learning cycle can be divided into novice, intermediate and advanced. Remedial training could potentially apply to any experience level; however, in the context of Army trade training, it refers to novice or basic training.

The studies which provided a quantitative assessment of the training effectiveness of simulators utilised novice welders [10, 25, 30, 31]. These studies provide evidence that a combination of simulation and live training was more effective than live training alone. Based on this outcome, and the results presented in Sections 4.2 and 4.3, it is apparent that the performance measurement and feedback provided by these simulators is useful for teaching novices a correct welding technique.

The utility of welding simulation as a remedial trainer would depend on the nature of the skill deficiency, and the extent to which it can be corrected through the feedback provided by the simulator. This feedback appears to be sufficient for addressing gross errors in technique, but may not be adequate for correcting more subtle errors (this is discussed further below). For the training of basic welding skills, remedial training is likely to be required by students who are struggling to make progress and find it difficult to correct even gross errors in technique. While the augmented feedback provided by simulation could benefit such students, remedial training should ideally include high levels of supervision, potentially on a 1:1 basis, to help students interpret the feedback and to ensure that students are using appropriate techniques.

Within Army trade training, specialist welding skills are characterised by the use of different types of metal compared with routine welding, the requirement for a higher standard of weld, and the need to weld on curved and raised surfaces. There is little direct evidence available from the papers reviewed that can help address this question. However, the basic principles for designing a simulator for training specialist skills are the same as discussed earlier, but applied to the specialist welding context; namely:

- Training must allow students to practise relevant skills,
- Training must include performance assessment,
- Students should be provided with feedback during and after training.

It should be relatively straightforward for simulators to provide a virtual representation of any weld type or welding situation. However, physically replicating the welding surface, and other aspects of specialised welding (e.g., welding in confined spaces) would be difficult to achieve. Higher standards could be required during assessment (e.g., setting narrower tolerances for critical parameters, as suggested in [10]), however the effectiveness of this strategy would be reliant on the accuracy with which the simulator can predict weld quality. This would also have implications for sensor accuracy.

As noted in Section 4.2, there appear to be some limitations with how weld quality was predicted. For example, in [22], the empirical data used to develop the neural network used to assess weld quality in the simulator was based only on T fillet welds on the same material. Consequently, it is plausible that this method may be less accurate when used to predict the weld quality for different contexts¹²; this is supported by the fact that instructors evaluating this simulator found it difficult to execute a successful weld. Mathematical models have also been used to assess weld quality; it is not known whether they provide sufficient accuracy for training specialist skills. A similar argument can be applied to the provision of feedback. Where the feedback is underpinned by the same data as assessment, then it is likely to suffer from the same limitations. Overall, it can be concluded that current simulators are unlikely to be useful for training specialist welding skills. Similar reasoning leads to the same conclusion for the training of intermediate and advanced welders. However while the preceding arguments are logical, they are not currently supported by empirical evidence, consequently this issue warrants further investigation.

¹² This issue is implicitly acknowledged by the authors, who note that the neural network was designed to be capable of incorporating new data for any special welding process or procedure.

5.3 What are the implications of using welding simulation for the role of the instructor?

While it has been suggested that the provision of augmented feedback can reduce the need for instructor intervention, there is no evidence that effective delivery of simulation-based training can occur with significantly fewer numbers of instructors. This is because many students are still likely to require instructor assistance in interpreting the augmented feedback and correcting their welding technique. Indeed, it has been suggested that augmented feedback is more suitable for self-reliant students, thereby freeing up instructors for greater individualised training for those who need it (e.g., remedial training)[8]. Consequently, while use of simulation may result in more efficient training and provide opportunities for increased throughput, it is unreasonable to expect large gains without any increase in the number of instructors. The example of novice welders using a can or grinder to support their elbow while they conducted simulated welds (Section 4.5.2) is a clear demonstration of the importance of appropriate supervision.

5.4 What is the optimum ratio of live:simulated welding?

A comparison of training outcomes between novice welders receiving 100% live training or a 50:50 mix of live and simulation-based training suggests that the combination of training methods is more effective than live training alone. Specifically, the mixed training method resulted in superior live welding performance following training, significantly better knowledge of welding and shorter overall training times (Section 4.5.2). Only one study examined 100% simulator training [31]. This study found that 100% simulation-based training gave similar outcomes to a 50:50 mix of live and simulation-based training for simple welding tasks (2F, 1G, 3F) but that the mixed training method was more effective for training the more difficult weld (3G), although both methods resulted in low pass rates in this case. This is consistent with the conclusions regarding specialised welding in Section 5.2 above. Overall, the amount of live training that can be replaced by simulation depends on the specific welding task; however, it is reasonable to conclude that effective training of basic welding tasks can be achieved using a significant proportion of simulation-based training. Beyond this, the idea of precisely defining an optimum mix of training methods may be flawed, because there are many factors in addition to the simulator that determine training effectiveness. These include student characteristics (e.g., aptitude), training design (e.g., scheduling) and work environments (e.g., learning culture)[45].

5.5 What level of fidelity and feedback does the simulator need to deliver effective training?

The question of fidelity and feedback is important, as higher levels of fidelity and more feedback features are usually associated with greater cost, yet may not be necessary to achieve the desired training outcomes. Reliable performance assessment and feedback is considered essential for effective training, but there is limited evidence on the type of feedback and level of fidelity required for welding simulators. While simulators provide a variety of visual, audio, or haptic feedback only two studies directly examined the impact of different types or levels of feedback on welding performance and neither of these examined different fidelity levels (Section 4.3). Some simulators used binary forms of feedback, which indicate if a weld is inside or outside critical parameters, but do not provide any graduation

to alert the welder that they are approaching these boundaries. This lacks realism, but the impact on training outcomes is unclear.

It is interesting to note that two of the studies that found evidence for the effectiveness of simulation-based training used simulators of widely different fidelity [10], [25]. The first study was conducted 40 years ago, employing simple technologies to provide feedback and relying on industry guidelines for the critical parameters in order to predict welding performance. The second study was conducted only three years ago and used a high fidelity simulator, but there is no evidence to suggest this provided better training outcomes. As discussed in [10], novice welders are initially incapable of using any of the feedback inherent in the welding task due to the difficulty in using the feedback to understand what changes in technique are required. Consequently, even rudimentary augmented feedback providing only basic guidance on required changes in technique may be sufficient to provide training benefits. This issue is worthy of further investigation.

5.6 Future research on welding simulation

This study has identified a number of gaps that need to be addressed by future research. These fall under areas of simulator use and evaluation; simulator design and development and cost-effectiveness. The gaps could be addressed through a mixture of experimentation, analysis, and SME input. These are described for the benefit of designers and users of welding simulation. They do not currently form part of DSTO's planned research program because it is not guaranteed that such research would result in cost-effective improvements to welding simulation

This study has found evidence that welding simulation can provide effective training for novice welders across a limited range of weld types. However, the relationship between training effectiveness, simulator fidelity, welding task, student experience and training design needs to be better understood. Potential studies include:

- Determining whether greater simulator fidelity will provide increased training benefit (noting that positive transfer of training was found for both low and high fidelity welding simulators, see Section 5.1).
- Measuring the training effectiveness of simulators over a wider range of tasks and student experience levels, including specialist welding techniques and advanced welders.
- Determining the optimum training design for the delivery of simulation-based training. The only studies to have examined a mix of live and virtual training used a 50:50 mix, with each method delivered in a single block. It is possible that another mix (e.g. 25:75 or 30:70 simulated:live), or the same mix but delivered in alternate blocks may be more effective.

Such research could also be useful in supporting future simulator design and development. There are several aspects requiring further investigation, including:

- Characterisation and assessment of successful live welding performance. This report has highlighted limitations in how simulators use the critical welding parameters to assess weld quality. More accurate models of welding performance may be required, particularly as current simulators appear to be poor at assessing the performance of

expert welders. This could be achieved by collecting empirical welding data over a wider range of welding parameters, as well as from expert welders.

- Determining which aspects of feedback (i.e., sound, weld pool appearance) are the most important in achieving effective training outcomes and the extent to which this factor depends on welding experience. Both of these research areas would be supported by the evaluation studies proposed above.

The third research area could examine the cost-effectiveness of welding simulation. This report has identified a number of areas where welding simulation may save time and money. However, only limited data were provided in support of these claims. The following research is proposed:

- Collecting training time and resource usage data from the evaluation studies proposed above.
- Conducting a broader systems level cost-benefit analysis of welding simulation, as described in Section 4.6.

6. Conclusion

This study has found that a combination of simulation and traditional methods can provide effective training for novice welders in basic weld types, as well as offering savings in time and resources, when compared to traditional training alone. However, there is as yet no evidence that simulation can be used to train more experienced welders or specialised welding skills. While simulation-based training may lead to greater training efficiencies, it is apparent that instructors will be required to make best use of the augmented feedback provided by these simulators, as well as continuing to monitor students' technique. Finally, while simulators offer a range of feedback options, it is not clear which of these options, is required for effective training.

This study has made a significant contribution to the state of knowledge regarding welding simulation, and to simulation-based training and the training of fine motor skills more generally. This is a result of examining the problem from several perspectives, including those of training organisations and researchers, across multiple disciplines including engineering and human factors and at different levels, ranging from the individual student to the training organisation employing simulation. Such an approach is needed in order to address all aspects of welding simulation that relate to the design, use and evaluation of training effectiveness.

This study has highlighted a number of issues that are likely to generalise to the training of other fine motor skills using simulation. Of particular interest is the need to characterise task performance in the live environment in order to model it appropriately in the simulator, and provide accurate performance assessment and feedback. This appears to be particularly difficult to achieve with welding, where performance is dependent on several variables and acceptable performance is associated with small tolerances in these variables. In spite of this, it is apparent that basic welding skills learned in the simulator still transfer to the live environment, resulting in some savings in time and resources. While future research may be required to better characterise welding performance, this study demonstrates that welding

simulators may not require high levels of fidelity to provide some training benefit; lower fidelity solutions may also provide effective training.

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Appendix A: Task analysis

Based on the data collected during the September 2012 training establishment visit, including hands-on experiences of welding and discussions with staff and students, two tasks analyses (one for each weld type) were conducted to identify the component tasks involved in GMAW and MMAW.

The first part of the task analysis consisted of breaking the welding process down into separate discrete cognitive (e.g., observe and interpret feedback such as characteristics of weld pool) and physical (e.g., adjust position of gun) tasks. These tasks were further analysed in order to identify those where simulation-based training could be expected to provide greatest improvement in performance. This was obtained by rating each task against two dimensions, 1) the extent to which successful completion of the task was critical for successful completion of the weld, and 2) the extent to which augmented feedback could be expected to improve performance. Each dimension was rated as low, medium, or high, using the following definitions.

Criticality:

- Low – Not essential to get this right for weld to be successfully executed; could be omitted and weld would still be acceptable.
- Medium – Important to get this correct or for this to occur, but errors and omissions were recoverable.
- High – Essential to get this correct for weld to be successfully executed. Errors would almost certainly affect weld quality.

Augmented feedback:

- Low – Augmented feedback was unlikely to improve this task. This is because the task was straightforward, the task already provided sufficient feedback, or the task was binary (that is, either it occurs correctly or it does not, with no need for subjective interpretation about the quality of its execution, for example putting on safety equipment).
- Medium – Augmented feedback may provide improvement above and beyond that expected to be achieved by repetition of the task.
- High – Augmented feedback has the potential to result in considerable improvement in the task, due to the task complexity or lack of intrinsic feedback.

This produced a 3 x 3 matrix. Tasks were categorised as having low, medium, or high potential for training via simulation according to Table 2. Cells with the highest potential payoff for training via simulation are those coloured green, where at least one dimension was rated High, and the other was Medium or High.

Table 2: Matrix for assessing simulation-based training potential

		Criticality		
		Low	Medium	High
Augmented feedback	Low			
	Medium			
	High			

Results from the task analysis suggested that the most critical tasks are:

- Hold gun in correct position
- Move welding gun along plate, observing and adjusting position and speed of gun if required
- Observing characteristics of the weld pool, sparks, and sound, adjusting position of gun if required.

These tasks are also those SMEs identified as some of the most difficult to learn for novice welders; consequently, these tasks would be expected to benefit the most from augmented feedback. Changes to the welding process, such as an adjustment in the travel speed, will result in immediate changes to the intrinsic feedback (e.g., visual characteristics of the weld pool and the welding sound). Consequently, SMEs and students noted that the provision of any augmented feedback in a simulator should reflect changes to the welding process in the same way (i.e. the feedback must be real-time). In summary, the task analysis has identified where and when the augmented feedback needs to occur, but not how. This is discussed in more detail in the main body of the report (Section 4.3 and Section 5.5).

A.1. Gas Metal Arc Welding (aka Metal Inert Gas Welding) task analysis

Task	Criticality to welding process	Potential for augmented feedback	Simulation-based training potential
1. Select equipment			
1.1. Select welding surface, e.g. plate	Medium	Low	Yellow
1.2. Check stick is appropriate length	Medium	Medium	Yellow
1.2.1. Trim stick if required	Low	Low	Red
2. Set machine parameters, e.g. amps, current	Medium	Low	Yellow
3. Commence welding			
3.1. Put on required safety equipment (glasses, mask, gloves)	Low	Low	Red
3.2. Hold gun in correct position	High	Medium	Green
3.2.1. At required angle	High	Medium	Green
3.2.2. With stick appropriate distance from plate	High	Medium	Green
3.3. Depress button to initiate welding	Medium	Low	Yellow

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4. Move welding gun along plate			
4.1. Observe distance between stick tip and plate	High	High	Green
4.1.1. Adjust position of gun on y-axis if required	High	High	Green
4.1.2. Trim stick if required	Low	Low	Red
4.2. Observe characteristics of weld pool			
4.2.1. Adjust position of gun on x-axis and z-axis if required	High	High	Green
4.2.2. Adjust speed of movement of gun on x-axis and z-axis if required	High	High	Green
4.3. Observe characteristics of sparks around rod	High	High	Green
4.3.1. Adjust position of gun on y-axis if required	High	High	Green
4.4. Observe characteristics of sound	High	High	Green
4.4.1. Adjust position of gun on y-axis if required	High	High	Green
4.4.2. Adjust machine parameters if required	Medium	Low	Yellow
5. Finishing weld			
5.1. Release button to cease welding	Medium	Low	Yellow
5.2. Remove safety equipment (optional)	Low	Low	Red

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A.2. Manual Metal Arc Welding (aka Stick Welding) Task Analysis

Steps involved in MMAW:

Task	Criticality to welding process	Potential for augmented feedback	Simulation-based training potential
1. Select equipment			
1.1. Select welding surface, e.g. plate	Medium	Low	Yellow
1.2. Select rod	Medium	Low	Yellow
2. Set machine parameters, e.g. amps, current	Medium	Low	Red
3. Insert rod			
3.1. Loosen top of welding gun	Low	Low	Red
3.2. Insert rod at correct angle	Medium	Low	Yellow
3.3. Tighten top of welding gun	Medium	Low	Yellow
4. Commence welding			
4.1. Put on required safety equipment (glasses, mask, gloves)	Low	Low	Red
4.2. Hold gun with rod perpendicular to plate	High	Medium	Green
4.3. Strike rod to initiate welding	Medium	Low	Yellow
5. Move welding gun along plate			
5.1. Observe distance between rod tip and plate	High	High	Green
5.1.1. Adjust position of gun on y-axis if required	High	High	Green
5.2. Observe characteristics of weld pool	High	High	Green
5.2.1. Adjust position of gun on x-axis and z-axis if required	High	High	Green

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5.2.2.Adjust speed of movement of gun on x-axis and z-axis if required	High	High	
5.2.3.Adjust machine parameters if required	Medium	Low	
5.3. Observe characteristics of sparks around rod	High	High	
5.3.1.Adjust position of gun on y-axis if required	High	High	
5.3.2.Adjust machine parameters if required	Medium	Low	
5.4. Observe characteristics of sound	High	High	
5.4.1.Adjust position of gun on y-axis if required	High	High	
5.4.2.Adjust machine parameters if required	Medium	Low	
5.5. Lift welding gun from plate to break contact	Medium	Low	
5.6. Remove safety equipment (optional)	Low	Low	
5.7. Chip away flux	Medium	Low	
5.8. Replace rod if required (optional)	Low	Low	
5.9. Recommence welding (optional; process repeats from Section 3)	As per Section 3	As per Section 3	

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19. ABSTRACT The use of simulation has the potential to provide safe, efficient and cost-effective welding training for the Australian Army and other training organisations. This report describes the outcomes of a DSTO study conducted to characterise key issues related to the use, design, and effectiveness of welding simulation. The study used a multi-method approach, including a literature review, discussions with staff and students at an Army trade training establishment, and a detailed analysis of the welding process. Results suggest that welding simulators can potentially provide effective training and save time and resources, when used in conjunction with traditional training. However, these findings appear to be restricted to novice welders due to limitations in how welding simulators assess performance and provide feedback. In addition, current calculations of the overall cost-effectiveness of welding simulation do not take into account factors such as staffing, infrastructure, and maintenance. The report discusses the implications of these findings for training and identifies areas for future research in this area.					