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An Investigation of Skill Acquisition under Conditions of Augmented Reality

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AN INVESTIGATION OF SKILL ACQUISITION UNDER CONDITIONS OF AUGMENTED REALITY

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ABSTRACT

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Augmented reality is a virtual environment that integrates rendered content with the experience of the real world. There is evidence suggesting that augmented reality provides for important spatial constancy of objects relative to the real world coordinate system and that this quality contributes to rapid skill acquisition. The qualities of simulation, through the use of augmented reality, may be incorporated into actual job activities to produce a condition of "just-in-time learning." This may make possible the rapid acquisition of information and reliable completion of novel or infrequently performed tasks by individuals possessing a basic skill-set. The purpose of this research has been to investigate the degree to which the acquisition of a skill is enhanced through the use of an augmented reality training device.

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INTRODUCTION

Augmented reality (AR) describes virtual environments that integrate rendered content with the experience of the real world (Majoros & Boyle, 1997). Typical applications incorporate "look-through" head mounted displays (HMDs) or stationary head up displays (HUDs). These kinds of displays permit the user to view the surrounding environment in a natural manner and simultaneously experience rendered images combined within the display. Virtual elements are made to appear as though they exist in the real space surrounding the user.

The virtual elements that are experienced in an environment of augmented reality are rendered appropriate to their surroundings (Klinker, Stricker & Reiners, 1998). There is evidence suggesting that augmented reality provides for important spatial constancy of objects relative to the real world coordinate system and that this quality of AR contributes to the transfer of knowledge (Neumann & Majoros, 1998).

Objects rendered in AR are consistent with a particular location in space (Klinker et al., 1998). This is especially well suited to equipment related tasks that are reliant on guidance by reference to documentation (Neumann & Majoros, 1998) or to a measurement standard. Augmented reality may lend itself particularly well to the performance of skilled tasks (Caudell & Mizell, 1992). As AR begins to move out of the domain of demonstration and closer to industrial application, it is of value to investigate the manner by and degree to which these environments support the acquisition of skills (Chung, Shewchuk, & Williges, 1999).

The Aviation Safety Reporting System indicates that 60 percent of maintenance-related reports concerned procedural errors, many due to negligence (Neumann & Majoros, 1998). There are indications that through integration of virtual environments into real-time task performance, motivation, interest, and transfer of learning can be enhanced (Azuma, 1997; Neumann & Majoros, 1998). The qualities of simulation, through the use of augmented reality, may be incorporated into actual job activities to produce a condition of "just-in-time learning" (Neumann & Majoros, 1998). In this environment the distinction between simulation and actual practice becomes blurred while their principles remain distinct.

Working within an environment of augmented reality, the human participant can be continuously provided with timely and relevant information (Bullinger, Bauer, & Braun 1997; Neumann & Majoros, 1998). For example, approved data is nearly always associated with aircraft maintenance tasks. This information can be provided to a technician during performance of the relevant task through AR and its currency can be maintained through software authoring (Neumann & Majoros, 1998). In other words, the approved data is always current and made instantly available through a manner that is transparent to the user.

Thus, the user may approach an AR supported task with current and appropriate data and may be elevated to approximate expert status when undertaking tasks that, while appropriate to the user's skills, may be otherwise novel. AR may, therefore, make possible the rapid acquisition of knowledge and reliable completion of novel or infrequently performed tasks (Neumann & Majoros, 1998) by individuals possessing a basic skill-set.

Data may be presented as context appropriate procedural text boxes that update automatically with the progress of a task (Neumann & Majoros, 1998). AR may also be employed to provide a graphically displayed job-appropriate measurement standard. This project will investigate the latter.

In aircraft sheetmetal fabrication, the acquisition of the skills necessary to satisfactorily install structural rivet fasteners is accomplished through tedious repetition. This process incorporates qualities of motor learning. Once acquired, this knowledge becomes extraordinarily persistent (Regan, 1997; Swezey & Llaneras, 1997).

During the skill building phase of structural rivet installation, the neophyte technician must repeatedly refer to approved completion standards in order to provide for both quality assurance of the task and for reinforcement of haptic information from the act of "driving" or "squeezing" the rivet itself. This requires that technicians set down their installation equipment; acquire a measuring device; employ and interpret the device; return the measuring device; and reacquire the riveting tools in order to proceed to the next fastener. During inspection procedures, only the installation component of the above task summary is omitted. That is, to unequivocally provide for the assurance of a nominally installed fastener, inspectors must employ a precision measuring device and reference to known completion standards.

Through the use of an augmented reality training device that provides a visual measurement standard, training technicians may be able to progress with confidence in the precision of their work. Additionally, they may progress without interruption of the "motor flow" of the training task.

Under conditions of actual production employing skilled technicians, fabrication tasks may be streamlined. For example, changing of rivet types (harder to softer and vice versa). Of significant importance is the implication that enhanced skill acquisition through the use of augmented reality generalizes to similar equipment-based tasks.

Statement of the Problem

Little investigation has been made into the use of augmented reality as an aid to manufacturing or inspection and few studies have been performed to investigate actual performance gains through the use of this medium (Chung et al., 1999). The purpose of this research will be to develop and conduct an experiment that will yield inferences with respect to the skill acquisition in a manufacturing task through the use of an augmented reality training device.

Review of Related Literature

Background and Applications of Augmented Reality

Requirements. In general, virtual environments refer to computer rendered, usually visual, representations of real-world objects with which a user can interact (Majoros & Boyle, 1997). These environments may be broadly divided into those that are and are not immersive (Majoros & Boyle, 1997). In immersive virtual environments, the real world is made opaque. Under these conditions the user interacts exclusively with and within a synthetic environment (Carr, 1995; Majoros & Boyle, 1997; Klinker, Stricker & Reiners, 1998). An example of the use of an immersive environment in training is the use of a head-mounted vision-based system of adequate fidelity to provide outside-of-harbor training in submarine handling for deck officers (Hays & Vincenzi, 2000).

Augmented reality (AR) is an environment that integrates rendered content with the experience of the real world (Majoros & Boyle, 1997). Chung et al. (1999) maintain that at its most basic, AR refers to the projection of virtual objects into three-dimensional space in such a way that the images appear superimposed over the real world.

Klinker et al. (1998) go further, suggesting that virtual elements must be composite with the real world; coexisting with real objects in a manner that is plausible to the user. For example, virtual objects must occlude and be occluded by real objects. Azuma (1997) offers a similarly stringent interpretation that, without respect to specific technologies, AR can be described as any system that provides for the combination of real and virtual objects; is interactive in real time; and provides for registration in three dimensions.

By these assertions, the rich environments of computer animation integrated with real action, as found in modern motion picture production, fail on two counts. They are neither interactive nor does their composition take place in real time. Two-dimensional virtual overlays can be integrated with video presentations of real objects so as to be interactive in real time. These compositions fall short of AR in that they are not rendered such that the user experiences the virtual elements as existing plausibly within the coordinate system of the real objects (Azuma, 1997; Klinker et al., 1998).

By these criteria, the common thread among the literature to characterize AR as virtual content superimposed on the real world (Haniff, 1999), in fact, overlooks an underlying consensus drawn from the spirit of the same body of literature which holds that AR describes virtual content *integrated within* the real world. Augmented reality and fully immersive virtual reality exist along a continuum of mixed realities (Klinker et al., 1998). Azuma (1997) and Klinker et al. (1998) assert that completely synthetic immersive virtual environments define one limit of the mixed reality spectrum while telepresence or fully real environments define the opposite. In this context, augmented reality may be characterized as the middle ground (Azuma, 1997; Klinker et al., 1998).

Goals of Augmentation

Typical visual AR applications incorporate "look-through" HMDs or stationary HUDs. These kinds of displays permit the user to view the surrounding environment in a natural manner and simultaneously experience rendered images combined within the display. Virtual elements are made to appear as though they exist in the real space surrounding the user.

Only recently has AR exceeded the domain of basic research and demonstration and become recognized as a potential industrial technology (Chung et al., 1999). Medical, manufacturing and repair, entertainment, and the military have been identified as promising industries for employment of AR for use in information transfer (Azuma, 1997; Chung et al., 1999).

Medical. In the field of medicine, augmented reality environments have been identified as particularly appealing to the specialty of surgery (Azuma, 1997). Practical applications under exploration include training and real time operational guidance through the superimposed registration of medical data (e.g., MRI, CT or ultrasound) (Bajura, Fuchs, Ohbuchi, 1992; Schumann, Burtescue, & Siering, 1998).

Bajura et al. (1992) describe the promise of incorporating apparent x-ray vision in the form of real-time three-dimensional ultrasound volume data with the physician's real-world view of the patient. As registration concerns are resolved (Psotka, 1995; Azuma, 1997; Chung et al., 1999), minimally invasive surgical procedures demanding of fine precision, such as needle biopsy, may be guided through superimposition of such information (Azuma, 1997; Schumann et al., 1998).

Manufacturing and Repair. Successful assembly, maintenance, repair, and overhaul of sophisticated systems is highly dependent on current technical data (Caudell & Mizell, 1992; Neumann & Majoros, 1998). As related in this chapter, augmented reality applications can facilitate data currency and retrieval through software authoring. Research has focussed on the provision of visually anchored textbox annotation and wire-frame superimposition to provide technicians with real-time in-task support to industrial processes (Caudell & Mizell, 1992; Azuma, 1997; Newman & Majoros, 1998).

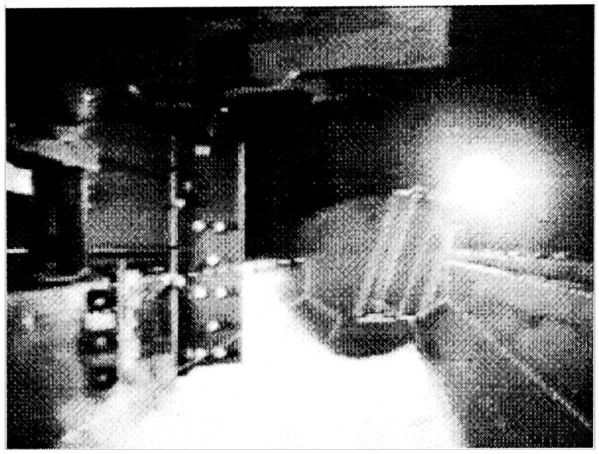

Figure 1. AR application employed to highlight the geometry of a shuttle orbiter's cargo bay (Drascic et al., 1999).

Annotation and Visualization. Potential AR applications include virtual annotation of real-world objects with both public and private data (Azuma, 1997). User position tracking and computer vision applications have been explored with respect to providing automatic retrieval and display of context relevant information (Azuma, 1997).

AR could find acceptance in general visualization tasks (Azuma, 1997). Architects might make use of augmented environments to visualize the impact of new structures, the joining of bridge spans, or to experiment with the virtual "removal" of existing structures (Azuma, 1997; Klinker et al, 1998). In environments of extreme lighting conditions, AR can be employed to help compensate for deterioration in contrast between objects such as visualization of the geometry of a shuttle orbiter's cargo bay while in orbit (Drascic, Grodski, Milgram, Ruffo, Wong, & Zhai, 1999) (Figure 1).

Equipment Piloting. AR can facilitate the teleoperation of machinery particularly where there exists significant distance or time delay between operator input/feedback registration and machine action (Azuma, 1997). As with sophisticated manufacturing

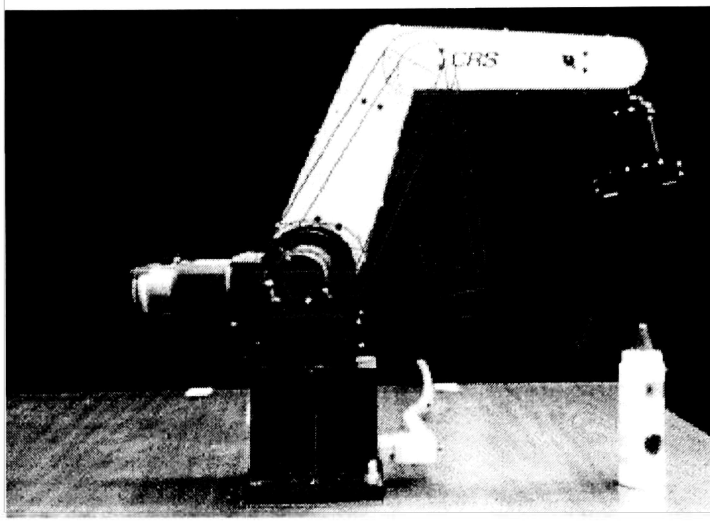

Figure 2. Using the ARGOS system, an operator interacts with a teleoperated robot by "grabbing' the robot's arm with a virtual hand and is able to preview its eventual location (Drascic et al, 1999).

processes, it remains impractical to employ automation in telerobotic operation within unstructured environments (Drascic et al., 1999).

Systems such as the *Augmented Reality through Graphic Overlays on Stereovideo* system (ARGOS) under development at the University of Toronto are intended to facilitate teleoperation tasks through AR-based user/machine interface (Drascic et al., 1999). ARGOS permits the user to interactively plan and preview task outcomes prior to scheduling of the task event (Drascic et al., 1999) (Figure 2).

Entertainment. The MIT Media Lab has developed a video-based environment Artificial Life Interactive Video Environment (ALIVE) (Azuma, 1997). In the ALIVE environment, users are able to reference their own image and surroundings on a large video monitor while interacting in real time with computer rendered characters (MIT Media Lab, 1995; Azuma, 1997) (Figure 3). Additionally, there has been effort to

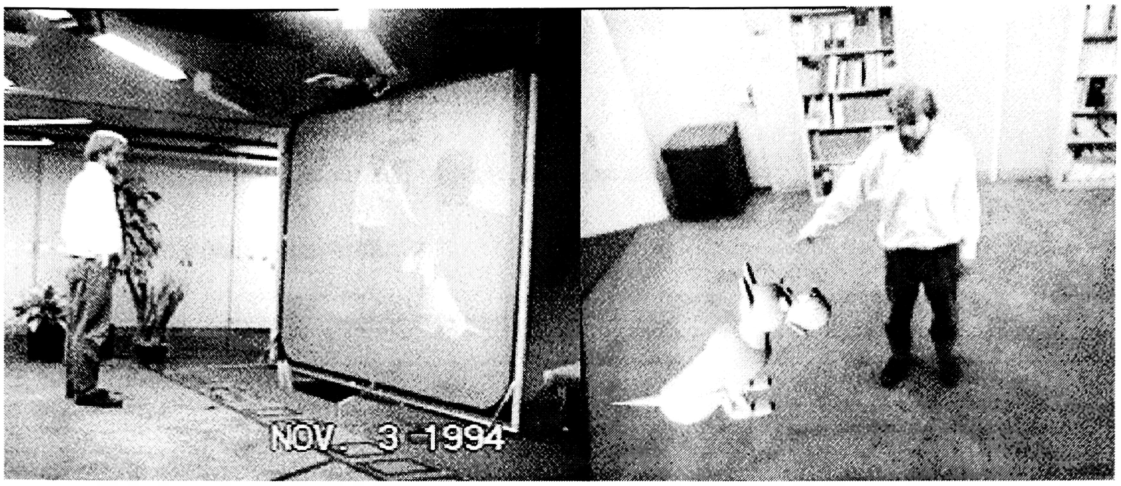

Figure 3. The ALIVE system allows users to interact in real time with autonomous animated characters. (MIT Media Lab, 1995).

develop systems that composite real actors with interactive virtual sets with the belief that the entertainment industry will be attracted to the cost and space savings associated with the reduction in set construction, storage, and disposal (Azuma, 1997). As greater advances in bandwidth are realized, distributed environments that merge multiple participants in composite environments could become more feasible (Schumann et. al., 1998) and applicable to multi-participant gaming and training environments.

Military Aircraft Applications. Military aircraft have incorporated HUDs and HMSs employed to merge graphically depicted information with the real world (Azuma, 1997). Through these systems, navigation and flight information can be provided to the pilot and weapons system targeting functions can be made interactive with the operator (Azuma, 1997). Developments in HMD technology will provide for incorporation of these features into the pilots helmet assembly (Azuma, 1997; Melzer & Moffit, 1997).

Summary. These broad application contexts underscore the basic tenets of AR. Augmented reality:

- Plausibly integrates virtual objects with the experience of the real world;
- Is interactive in real-time;
- Is not exclusive to specific technologies.

Perception, and the Registration Problem

Precise calibration and tracking are significant problems in the application of AR (Azuma, 1997; Schumann et al., 1998; Chung et al., 1999). Compositing the real environment with the virtual such that it is congruent with the manner by which a user accepts the natural world is a primary tenet of AR and the human eye is not easily deceived. At the fovea, the eye can resolve alternations between light and dark at 0.5 minutes of arc. Thus, disparities of a single pixel between real objects and their overlaid virtual companions are easily detected (Schumann et al., 1998).

Registration errors can be broadly classified as those that occur when the user's viewpoint is stationary and those that occur when the viewpoint is in motion. These are termed *static* and *dynamic* registration errors, respectively (Azuma, 1997). The literature provides for a number of elegant insights into minimizing the influence of these errors.

Dynamic Errors. Use of electromagnetic head tracking devices in HMD applications are problematic in AR (Schumann et al., 1998) and account for a significant source of dynamic error. Recent research in AR-based inspection by Chung et al. (1999) initially attempted to employ a binocular HMD incorporating an electromagnetic head tracker. The researchers found that the tracking system was inadequate for the precise alignment of the virtual object with the workpiece. Additionally, the virtual image appeared to “float” above the part rather than “merge” with it.

Other tracking technologies such as infrared, ultrasonic, and vision-based systems are capable of sufficient accuracy but current applications fall short in system response time and, for vision-based systems, upon reliance of the presence of tracking marks (Schumann et al., 1998). Vision-based systems hold promise, however, as the least susceptible to interference in industrial environments (Kim, Richards, & Caudell, 1997).

System lag, an additional source of dynamic error, is particularly difficult to resolve in look-through HMD systems (Azuma, 1997). In video-based systems where the virtual content is digitally merged with the real-world video stream, it is a reasonably small matter to compensate for system lag by introducing the same delay into the real-world stream (Azuma, 1997). Here it is left to the user to resolve disparities between display system lag and tactile/proprioceptive experience of the environment. In look-through HMDs, the effect of display lag is that of the virtual image trailing behind the apparent movement of real-world objects (Bajura et al., 1992; Azuma, 1997).

An additional problem encountered with video-based systems is that the cameras used to sample the real-world environment are typically located where the user’s eyes are not. Camera location displaces the user's "virtual" eye. This has been shown to effect coordination and speed in manual tasks (Rolland, Biota, Barlow, & Kancheria, 1995). Thus, an additional dynamic registration error is introduced in proprioceptive conflict (Azuma, 1997). While there is evidence of adaptation, there also exists evidence of disturbance to natural hand/eye coordination upon removal of the apparatus (Rolland et al., 1995).

In practical use, the level of required registration accuracy and work volume is dependent on the application (Caudell & Mizell, 1992). Research in AR supported manual manufacturing conducted by Caudell and Mizell (1992) of Boeing Computer Services accomplished tracking calibration for their application through use of a stationary calibration device.

Prior to beginning trials, the participants placed their heads into a forehead brace and, while wearing a look-through HMD, visually aligned a circle on an angled formboard with sighting holes on the stationary calibration panel. By adjusting viewing distance to align the circle with the vertical and horizontal cutouts in the sighting hole, the display system was able to acquire information about the HMD's position relative to the workpiece. Upon completion of the calibration procedure, the stationary calibration board was removed and it was found that tracking performance was adequate for the completion of experimental tasks within the limited experimental work-volume (Caudell & Mizell, 1992).

In more recent research, Chung et al. (1999) overcame this problem by eliminating the head-tracking feature completely. In this research, the stimulus constituted a wire-frame virtual overlay that indicated measurement locations on real parts of varying contours. The experimenters first established each participant's dominant eye. Covering the non-dominant eye in order to produce monocular vision, each participant then provided their own continuous calibration by adjusting their head position to align the virtual overlay with the corresponding workpieces.

In both examples, whether for initial system calibration or for continuous self-calibration, there is a priori acceptance that the participants themselves are reliable in establishing the correct relationship between virtual and real visual elements. With some further inspection in the literature and control through apparatus design, the current research will incorporate this acceptance of participants ability to register and make use of invariant (Lintern, 1991) and emergent (Elvers & Dolan, 1995; Carswell & Wickens, 1996; Wickens & Carswell, 1995) qualities of the visual environment for the purposes of establishing reliable relationships between virtual and real objects.

Static Errors. Four main sources of static error are optical distortion, errors in the tracking system, mechanical misalignments, and incorrect viewing parameters (Azuma, 1997). Focusing apparatus used in the construction of displays provide for relatively little distortion near the center of the field of view (FOV). Toward the limits of the FOV strait lines can become curved through optical distortion (Melzer, & Moffit, 1997; Kijima & Ojika, 1997). While it is possible to map and compensate for these errors, doing so is a nontrivial pursuit and one whose resource demands can introduce processing lag and, thus, dynamic error into the system (Azuma, 1997).

The act of the user moving about the work volume introduces design difficulties in viewing parameters. It is more practical to develop an optical system that provides good registration from a single than from several viewpoints (Azuma, 1997; Siebert & Kühner, 1998). That which looks satisfactory from one viewing angle, through tracking error and optical distortion, may deteriorate upon moving to another position (Azuma, 1997).

Mechanical misalignments constitute disparities between the orientation and compatibility of system components. For example, if the structure of the optical components are such that they cannot maintain sufficient rigidity, subtle distortions will be introduced for which compensation may be impractical (Azuma, 1997).

The same limitations that cause tracking systems to introduce dynamic error are also responsible for static error. Because a tracking system responsible for static registration error would theoretically require its own tracking system of greater accuracy to dampen the imprecision, it becomes evident that these errors can be the most insidious stumbling blocks to apparatus design (Azuma, 1997).

Learning with Respect to Virtual Environments

Skill acquisition and transfer research carried out at the University of Minnesota by Kozack, Hancock, Arthur, and Chrysler (1993) sought to investigate knowledge transfer under conditions of immersive VR. At the time of their study, the authors indicated that, despite the emergence and portrayal of VR as a valuable approach to training, there existed scant empirical findings with respect to perceptual-motor task transfer.

The experiment measured differences in transfer of learning between three groups performing a visually guided motor task. One group received no training, a second received real world training, and the third underwent immersive VR training. The VR training group interacted exclusively within the immersive environment. That is, without regard to proprioception, all feedback associated with grasping and moving of objects was accomplished through visual reference to the synthetic environment. The apparatus incorporated no haptic features. The results found no significant differences in skill transfer for training type. In discussion, the authors expressed concern that participant interface with the VR system with respect to operation and registration may have introduced a significant confound.

Heller, Calcaterra, Green, and Brown (1999) undertook research to investigate the degree to which vision dominates in intersensory (visual/haptic) size conflict resolution. Heller et al., (1999) found it to be normal for senses to work in cooperation. The authors assert that visual dominance is obtained under carefully constructed laboratory conditions where normal cues are distorted by experimental apparatus. Participants in this research did not exhibit visual dominance when exposed to conflicts between vision and touch.

Had the research of Kozak et al. (1993) been designed to investigate skill transfer for a similar task through use of an AR training system, the AR treatment group might have interacted with real world objects while being exposed to contextual guidance from the AR portion of the environment. Rendering and registration problems associated with the state of the art in equipment would likely have been problematic but the transfer results might have been significantly different.

General Motor Learning and Skill Acquisition

Providing information feedback is critical to the acquisition of motor skills (Kendrodle & Carleton, 1992). Without respect to specific methods of delivering this information, virtual environments or otherwise, this is described as feedback from the environment that provides information about the performers actions (Todorov, Shadmehr, & Bizzi, 1997). Todorov et al. (1997) broadly characterize the types of information delivery that have undergone study as knowledge of results (KR) and augmented feedback; depending on whether the information presented is intrinsic, for KR, or artificially generated.

Gentile (1972) describes KR as information feedback with respect to the outcomes produced by a movement. Vander Linden, Cauraugh, and Greene (1993) and Newell and Carlton (1987) blend the distinctions between KR and augmented feedback. The former research focussed on the differences in efficacy between KR and providing knowledge of performance (KP). KP is defined in Gentile (1972) as feedback that delivers information with respect to the movement itself.

Vander Linden et al. (1993) examined acquisition of an arm swing task. Participants were required to replicate a force schedule that was displayed on an oscilloscope incorporating an overlay depicting the desired force trace. Three treatment groups received feedback after each trial, after every other trial or concurrent with each trial. In acquisition trials, the concurrent feedback group displayed less RMS error than the complement, which did not differ. During immediate and 48-hour retention tests in the absence of kinetic feedback, lowest error was found among the 50% feedback group with the highest error found among the concurrent group. The results indicated that concurrent feedback might not be useful if task performance is expected to be exclusive of feedback.

Newell and Carlton (1987) examined the degree to which kinetic and criterion information presented as KR in augmented feedback hastened acquisition of an isometric task. Over two experiments, participants were required to first reproduce gausian and then less predictable force-time traces through a finger press task. KR feedback was provided as verbal force-time trace, computer generated force-time trace with a criterion overlay, and computer generated and verbal force-time trace.

In gausian trials, the verbal feedback group experienced the greatest error rate while there was found no difference between either the criterion or the visual/verbal feedback group. The subsequent experiment found significantly fewer errors in the group receiving criterion information. In both experiments, the effects remained unchanged for no stimulus trials (Newell & Carlton, 1987).

In discussion, the authors suggest that manipulation of task constraints (criterion overlay) and the participant constraints (predictability of the task) effected the degree to which the criterion overlay was useful for acquisition of the task. Additionally, when the task is predictable, it is the augmented feedback that is of greatest use in guiding task outcome. It is when the task constraints are unfamiliar that prescriptive criteria become most useful (Newell & Carlton, 1987).

For non-isometric motor tasks and those of high degrees of freedom, improved skill acquisition through augmented feedback has not been indicated (Todorov et al., 1997). In multiple degree of freedom tasks incorporating high cognitive loading, augmented feedback has not been shown to transfer well to the real world in the absence of the stimulus (Lintern, Roscoe, & Sivier, 1990).

One readily conceptualized example of an effort to employ KP stimulus in training is the use of videotape recordings of a tennis player performing a serve. Shown repeatedly to training players. This technique is intended to import information regarding the quality of the movement itself rather than the outcome of the eventual location of the ball (Kendrodle & Carlton, 1992). The feedback was suggested to improve performance for expert players but was of no significant benefit to novice and intermediate players.

Kendrodle and Carlton (1992) report that an overlooked variable in the majority of prior empirical studies involving video feedback is that of the role of attention riveting cues. The authors describe *cues* as stimuli, intrinsic or extrinsic, that focus the performer on those parts of the task that are relevant to the outcome. The learner must be able to register and interpret salient information and make appropriate adjustments during training in order to acquire operational effectiveness.

Invariant Qualities. The ability to acquire and transfer of novel skills suggests that through performance of one task – practice and training- one can ultimately and reliably perform another; the task for which one trains (Lintern, 1991). Practice of a tennis stroke at slow peed is expected to generalize to successful performance in normal play. Likewise, children are taught to draw large letters with the expectation that they will gather the ability to create the smaller characters typical of adult writing (Goodbody & Wolpert, 1998). Transfer of skill is based on some similarity between training experience and operational performance and on the learner's ability to identify and make use of those similarities that are relevant to the effect of transfer (Lintern, 1991).

In the article "An Information Perspective on Skill Transfer in Human-Machine Systems," Lintern (1991) relates and expands on Gibson's concepts of *invariant* relationships among tasks and their bearing on transfer. Invariant relationships can be characterized as those properties which remain unchanged across events as other properties change. Through practice, the theory holds, learners develop greater sensitivity to perceptual changes in those qualities that are to be held invariant. These qualities may not be explicit. For example, those who are highly skilled at a task are frequently unable to articulate the information necessary for its performance (Lintern, 1991).

Identifying and maintaining unchanged those qualities of a training task which are critically invariant to the operational task should provide for high transfer even if many features of context or environment are dissimilar (Lintern, 1991). However, there exists confusion within the literature with respect to transfer as experiments that should demonstrate it, fail to do so or contradict (Lintern, 1991).

Proximity Compatibility and Emergent Features. The *proximity compatibility principle* (PCP) can be described as a guideline to establishing relevance between display design and the task for which it is intended to support (Wickens & Carswell, 1995). PCP relies heavily on two families of similarity or *proximity*; *perceptual* and *processing* (Wickens & Carswell, 1995).

Information sources share greater perceptual similarity, and convey greater task-related information the more closely they are positioned to one another and the more that they share similar attributes (dimension, orientation, length). The degree to which sources indicate information related to the same task is descriptive of their mental or *processing* proximity. PCP suggests compatibility between these dimensions; indicating that close processing is best paired with close perceptual proximity (Wickens & Carswell, 1995).

Integration and comparison is made easier for the user by configuring information sources such that they are near to each other and share common attributes (Wickens & Carswell, 1995). Wickens and Carswell (1995) indicate that the savings, described in terms of *information access cost*, can be realized in decreased head and eye movements and attention through providing increased spatial proximity and maintenance of sources within close visual angles.

Emergent features describe those that come into existence through the relationships between display elements. The value of emergent features lie in their ability to import direct task cues that, in their absence, would require mental comparison of data values (Wickens & Carswell, 1995). Task related emergent features can be thought of as providing "visual shortcuts for the mental integration of data values" (Carswell & Wickens, 1996, p. 20).

Elvers and Dolan (1995) found in experimentation that compared task performance by reference to configural displays and separated displays incorporating emergent features that the emergent feature was of greater support to tasks performance than was display type. PCP indicates that the demands of the task, with respect to integration, should dictate display configuration (Wickens & Carswell, 1995). The current research will seek to apply PCP in design of a task relevant display. By providing high task proximity through emergent features incorporated in design of the AR stimulus, it is anticipated that these will present useful invariant qualities that will enhance skill acquisition and transfer.

Compositing Real and Virtual Elements. Wise and Sherwin (1989) investigated the effect of the near field presence of virtual imagery on the ability of participants to discriminate between apparently distant objects presented, through natural collimation, at optical infinity. Findings indicated that, under conditions of primarily binocular vision and where virtual objects maintained good contrast, the virtual displays did not reduce capacity to discriminate between similar virtual object types.

Participants compared primary and secondary stimuli; the former rear projected 14 m ahead of the viewer and the latter in the near field. To provide for focus as the only cue for distance, both primary and secondary stimuli were rendered the same visual size. It was found that the closeness of the secondary stimulus was not detrimental to discrimination performance. (Wise & Sherwin, 1989).

Ellis and Menges (1997) likewise investigated visual performance with respect to objects at optical infinity. Dividing groups into monocular, binocular, and stereo vision treatments, the study employed a look-through HMD that presented virtual objects rendered at an apparent distance of 58 cm to simulate an industrial application. By sliding an axially oriented light-tipped rod, participants attempted to position the rod directly under the apparent location of the virtual object.

Results indicated that stereo and binocular vision tended to provide for more reliable performance than did monocular. Of interest to the authors was the indication that the distant wall surface seemed to influence the apparent position of the monocular stimulus (Ellis & Menges, 1997).

Design solutions can draw upon these indications that apparent size and location relationships, and as described with respect participant HMD self calibration in Chung et al. (1999), to provide for location constancy queues in merging virtual objects with the view of the real world.

The literature indicates that additional strengthening of merging of virtual to real in the augmented environment can be realized through object occlusion (Bajura et al., 1992; Azuma, 1997; Klinker et al., 1998). Rendered objects must affect and be affected by the real world object whose space they appear to share (Bajura et al., 1992; Azuma, 1997; Klinker et al., 1998). Therefore, by providing for even a simple occlusion management feature, it should be possible to enhance the impression of the location in space of a virtual stimulus.

Control of Registration Errors. Wise and Sherwin (1989) minimized optical static registration errors through natural collimation. By employing a series of mirrors to direct the projected virtual image over a distance sufficient to effect optical infinity, the apparatus circumvented the need for collimating lens optics. In Chung et al. (1999) the shifting of head tracking responsibility to the participant effectively eliminated the most severe (Azuma, 1997) dynamic errors. By employing the lessons of both studies, it should be possible to eliminate the most severe registration errors through use of compatible optics and by employing a rigid stationary HUD isolated from and positioned relative to an immovable workstation.

Stimulus Design for High Display Proximity and Support of Transfer. The literature suggests that invariant qualities are useful to transfer though their commonality between training and operation tasks (Lintern, 1991). The current research makes the assumption that the participant, through reference to a virtual measurement device that closely approximates the dimension of the finished rivet, can register nominal completion of the task.

Additionally, the assumption is made that the change of the geometric features of the rivet during installation in close apparent proximity to the virtual stimulus constitutes a rich emergent feature between the shape of the rivet tail and the stimulus and that this feature is invariant to the task. Providing the high task proximity invariant as an emergent feature should enhance the salience of those qualities and provide for task acquisition.

Statement of the Hypotheses

There exists research suggesting that objects rendered in augmented reality acquire salient qualities with respect to the enhancement of skill acquisition. It is hypothesized that this effect on skill acquisition can be detected and measured.

It is anticipated that the study will show that the group employing an augmented reality training device will display a more rapid acquisition of skills and more consistently precise work than the complement of the sample.

METHOD

Participants

Participants consisted of ten female and 20 male undergraduate and graduate students from Embry-Riddle Aeronautical University. Participant age ranged from 19 years to 31 years old. The mean age of the sample was 23 years old. The median age of the sample was 22 years. Participants were screened for; right-handedness and normal/corrected near-field vision acuity. Additionally, participants were screened for normal color vision and for naivete to solid rivet installation. Participants were not disqualified based on prior experience with the installation of non-structural "pop" rivets.

Instruments

Display. Participants installed solid aircraft rivets while observing the work volume through a stationary HUD incorporating a partially silvered, 50% reflective combiner. The HUD combiner bracket was secured to the wall surface immediately behind the workstation. Overhead installation of the combiner permitted unobstructed arm movement beneath the display. This mounting method also served to limit static error by isolating the HUD from vibration associated with the operation of the complement of the apparatus. The combiner was positioned to permit an eye distance from the work piece of 23in (Ellis & Menges, 1997). Provisions were incorporated for vertical angle and rotational adjustment of the combiner.

Rendering of the AR stimulus was provided through use of a 533nm light emitting diode illuminating a slide on which was printed a negative image of the virtual object. The projector assembly containing both the light source and the image slide were secured approximately eight inches above the HUD combiner and incorporated no lens optics. Focused workstation lighting and ambient light were adjusted for contrast control between the virtual stimulus and the workpiece as well as for management of combiner glare.

AR stimulus (Figure 4). The augmented reality stimulus consisted of a virtual ring depicting the tolerance for finished diameter of a properly installed rivet for the experimental application; 0.230in inside diameter and 0.250in outside diameter. This tolerance incorporated the 0.234in nominal dimension of a finished rivet for this application (Department of Transportation, 1998) while providing for a region that was both discernable through reference to the AR stimulus and that was easily interpreted on the traditional measurement device (Figure 5). The display and workstation were secured to allow the participants to adjust their eye position for alignment the virtual object such that it appeared to rest directly upon workpiece (Caudell & Mizell, 1992; Chung et al., 1999).

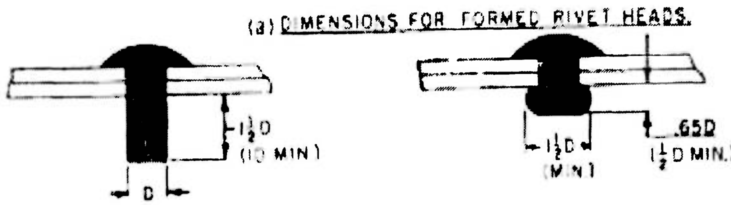

Figure 4. Nominal dimensioning of a finished rivet. (Department of Transportation, 1998).

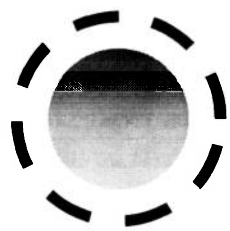

Figure 5. Representation of AR stimulus depicted with undriven rivet in center. Midline of ring symbolizes nominal finished rivet dimension while outside and inside diameter indicate tolerance.

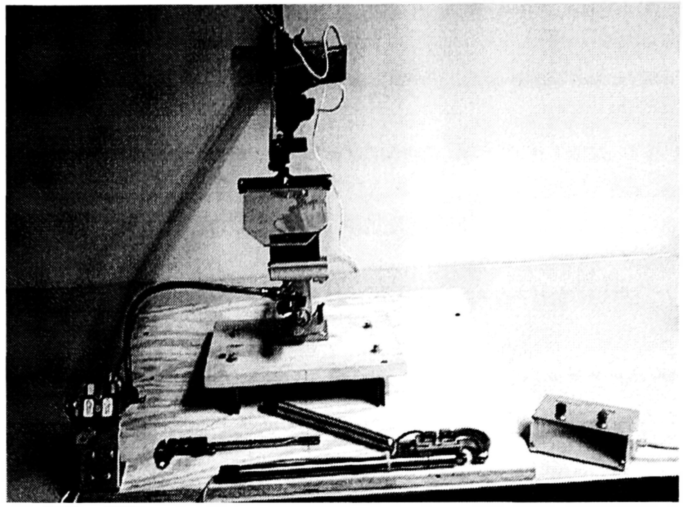

Figure 6. Experimental workstation showing virtual object projector (top), HUD combiner (forehead rest removed for clarity), hydraulic vice assembly with card installed, vice closure valve (left) digital caliper and rivet squeezer (center), and perceived rivet quality reporting buttons (right).

Workstation. The workstation consisted of a 30in high bench surface on which a stationary vice was mounted. The vise was mounted at an angle sufficient to provide both for a comfortable, task appropriate arm-reach and working angle (Kroemer & Grandjean, 1997). Additionally, this configuration provided for a more nearly parallel angle to the HUD combiner. The vice was modified to permit semi-hands-free operation through use of a foot pedal operating a hydraulic actuator. Vice closure was scheduled through actuation of a release valve operated by the participant's left hand. This feature was incorporated to prevent injury to participants' fingers and to trigger start-time of subsequent trials (Figure 6).

Workpiece. Each workpiece consisted of a 3in square *card* fabricated from 0.063in 6061 aluminum. Alignment guides were incorporated into the jaws of the stationary vice for precise positioning of each workpiece. In each card, a 5/32in hole was located above the vice jaws to accommodate one MS20470A5-5 rivet of dimensions 5/16in long by 5/32in diameter. Subtracting for the thickness of the 0.063in substrate, this provided for a *stickthrough* length of approximately1/4 inch. Finally, each card used in experimental trials was coated with flat black paint to provide for satisfactory contrast between the card, rivet, and the 533nm virtual object.

Occlusion management trigger. Occlusion management was provided through use of an electronic switching circuit that controlled the current delivery to the laser diode. The circuit interrupted the power supply to the diode at any time an object occupied the region directly above the workpiece. This established the virtual object as occupying an apparently constant position in space directly on top of the workpiece (Bajura et al., 1992; Azuma, 1997; Klinker et al., 1998).

A Type III laser diode was employed to provide a light trigger circuit for detection of objects in the region immediately above the rivet. A single beam was passed approximately 1/4 of an inch from the rivet tail and was trained on a photoresistor. Any object positioned such that the beam was broken, interrupted the light source falling on the photoresistor which, in turn, triggered circuitry scheduling an interruption in current to the image light source. This removed the virtual object from view for as long as any real object occupied “its” space.

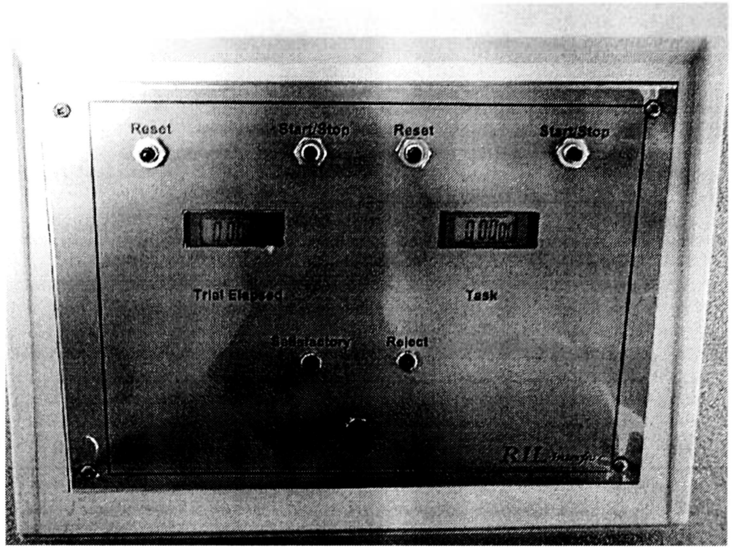

Figure 7. Experimenter's panel incorporating elapsed trial timer (top left), time-on-task timer (top right), perceived rivet quality indicator lights (center left and right), and "reset all" button (bottom).

Inspection reporting. A box incorporating pushbuttons with corresponding indicator lights was located immediately to the right of the vice assembly for participants to use in reporting their impression of the quality of each finished rivet. Depressing a button, coded each for satisfactory or for unsatisfactory, both illuminated a corresponding light on the experimenter's panel and triggered the stop time for each trial (Figure 6).

Experimenter's panel. Positioned behind and to the right of the participant, the experimenter's panel incorporated two digital timers for *elapsed trial time* and for *time-on-task* measurement. The panel also incorporated two lights corresponding to the inspection-reporting buttons located at the workstation. Finally, the panel included a

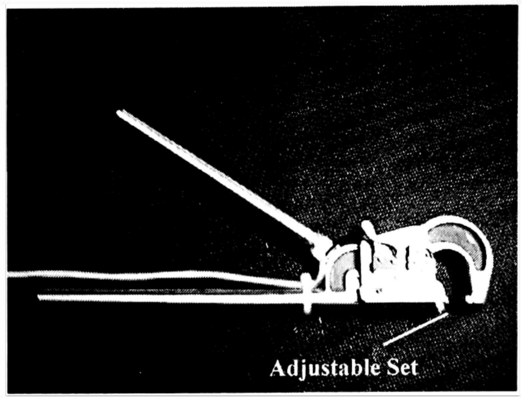

Figure 8. A common hand rivet squeezer modified to record time-on-task

single reset button that reset both timers and extinguished the inspection reporting lights at both the workstation and at the experimenter's panel (Figure 7).

Installation and inspection tools. Each rivet was installed through use of a common hand rivet squeezer. Height of the tool's *set* was adjusted and secured by the experimenter to provide for equal handle travel for all trials (Figure 8). The position of the adjustable set was such that participants were able to squeeze a rivet to as much as .280; .04 beyond the nominal dimension. The rivet squeezer was modified to trigger a timing device employed to measure time spent in actual application of work.

Traditional measurement device. During experimental trials, those participants assigned to the *traditional measurement device* group made use of a common pair of six-inch digital calipers. The same measurement device was employed for initial training of all participants (Figure 6).

Experimental Design

The experiment consisted of a one-way between groups design incorporating a single three-level independent variable for measurement device: *no measurement device; traditional measurement device;* and *AR measurement device.* Three dependant variables existed for (1) *precision* (absolute finished rivet diameter measures along the lateral axis), (2) *trial elapsed time,* and (3) *time-on-task* (actual work applied in seconds per trial).

Scoring for the precision DV was accomplished by a disinterested third party expert in both sheetmetal fabrication and in application of precision measurement devices. It was concluded that a single measure along the lateral axis of the finished rivet was sufficient with respect to the precision DV as:

- The materials selected and the installation equipment sufficiently constrained the degrees of freedom for the task such that rivets produced were reasonably round.
- The experimental environment itself restricted convenient application of the digital calipers to a lateral measure only.
- Participants were instructed to be vigilant for and "to do [their] best" to produce a round rivet.

Procedure

Participants were recruited from the Embry-Riddle Aeronautical University student community. Following consideration and signing of a notice of informed consent, participants underwent identical training sessions. During training, each participant was instructed with respect to:

- Operation of the hydraulic vice;

- Handling, and use of the trial workpiece cards;
- Handing and application of the hand rivet squeezer;
- Handing, application, and interpretation of the digital calipers for measurement of installed rivets along their lateral axis.
- Instruction with respect to evaluation criteria of finished rivets for the tolerance of 0.230in to 0.250in.

During training, Participants were guided verbally through the rivet installation procedure until meeting a criterion of two consecutive nominally installed rivets. Each participant was then randomly assigned to one of three treatment groups. As a control for experimenter bias, participants were assigned to a treatment group only after completion of training.

Participants assigned to the *no measurement device* group received instruction for signaling the beginning and end of trials and for use of the *perceived rivet quality reporting* equipment (i.e., *trial sequence* only).

Participants assigned to the *traditional measurement device* group received instruction for trial sequence. Initial training provided for familiarization with the digital calipers. Additionally, traditional measurement participants were instructed to make use of the digital calipers after each squeeze event for evaluation of their fasteners.

Those participants assigned to the *AR measurement device* group received instruction for trial sequence. Additionally, participants were familiarized with the features of the virtual stimulus.

Regardless of treatment group, participants were instructed to "do [their] best" to produce, with as much precision as possible, a round finished rivet within tolerances for finished diameter. Additionally, it was stressed that the installation of each rivet should be accomplished as rapidly as possible with as few squeezing events as necessary.

Although active for the AR treatment group only, all participants viewed the work-volume through the HUD combiner. Each participant completed 20 trials. To control for effects relating to anticipation of trial block completion, participants were not informed of the number of trials.

Before the beginning of each trial block, participant eye-height was set by adjusting seat height while referencing a string positioned in front of line marked on the wall immediately behind and above the workstation.

Prior to beginning each trial, participants opened the vice by depressing a foot pedal. Participants were instructed to align each workpiece card in the vice's jaws such that the tail of the rivet was positioned above the vice's jaws and facing them. Each trial commenced upon depression of the release valve by the participant. This action both scheduled vice closure and started the *elapsed trial time* digital timer located on the experimenter's panel. Participants then applied the hand rivet squeezer to install the rivet.

Each participant was required to evaluate the quality of each rivet installation in the manner appropriate to his or her treatment group and make further application of the hand rivet squeezer as necessary to produce a nominal finished rivet. Each trial concluded upon depression of a perceived rivet quality reporting button. This action allowed coding of perceived rivet quality but was employed primarily as a method of establishing trial completion.

Following each trial, the experimenter recorded scores, reset the timing equipment and, from a concealed location, handed the succeeding workpiece card to the participant. This method was employed to provide the experimenter with time to record scores and to prevent participants from anticipating the number of trials per trial block.

Following completion of trial blocks, each participant was provided with a prepared debriefing statement indicating intent of the study and the source through which each could obtain results of the experiment.

ANALYSIS

Data

Three dependent variables (precision, trial elapsed time, and time-on-task) were collected for ten participants per level of the independent variable. Additionally, *decision time* was examined by correcting trial elapsed time value for time-on-task. Each participant's trial block consisted of 20 trials. There were no missing data for any trial blocks. These data were tested for significance through examination using one-way analyses of variance (ANOVA).

Precision.

The mean precision (lateral diameter of finished rivets) for *no measurement device, traditional measurement device*, and *AR measurement device* were 0.237, 0.243, and 0.241 inches, respectively. These means do not differ significantly using a one-way analysis of variance (ANOVA), $F\ (2,27) = 0.685$, $p = 0.512$. Thus, measurement device does not affect the precision of this rivet installation task (Figure 9).

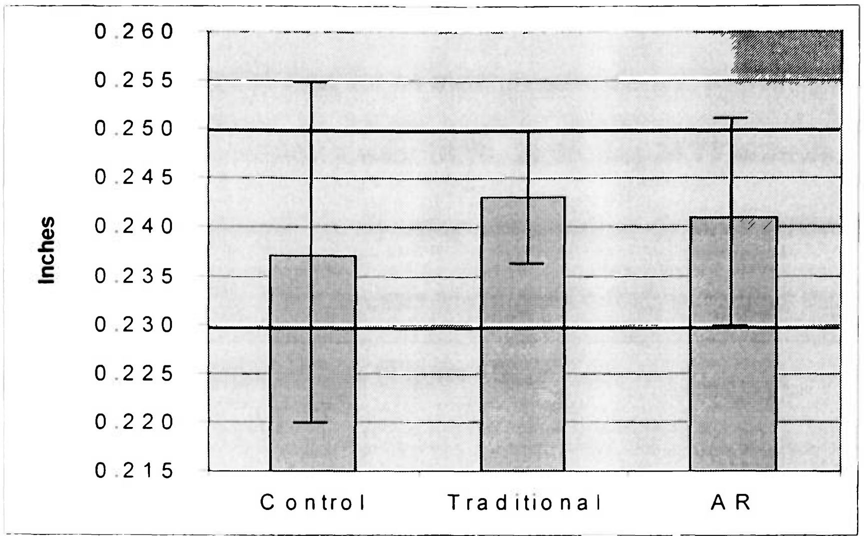

Figure 9. Graph depicting means and standard deviations for *precision*. Dark lines indicate tolerance region for a satisfactory rivet.

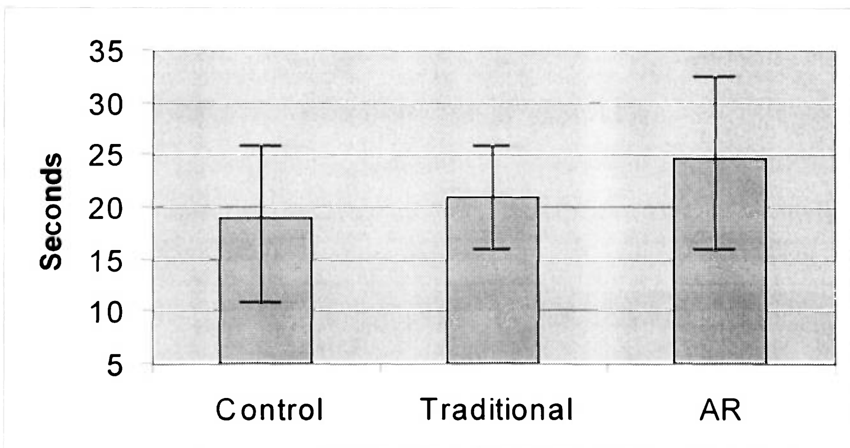

Figure 10. Graph depicting means and standard deviations for *trial elapsed time*.

Trial elapsed time.

The mean trial elapsed time for *no measurement device, traditional measurement device*, and *AR measurement device* were 18.98, 21.06, and 24.72 seconds, respectively. These means do not differ significantly using a one-way analysis of variance (ANOVA), F (2,27) = 1.448, p = 0.253. Thus, measurement device does not affect the elapsed time to complete this rivet installation task (Figure 10).

Time-on-task.

The mean time-on-task for *no measurement device, traditional measurement device*, and *AR measurement device* were 5.57, 4.90, and 5.97 seconds, respectively. These means do not differ significantly using a one-way analysis of variance (ANOVA), F (2,27) = 0.430, p = 0.655. Thus, measurement device does not affect the time-on-task during completion of this rivet installation task (Figure 11).

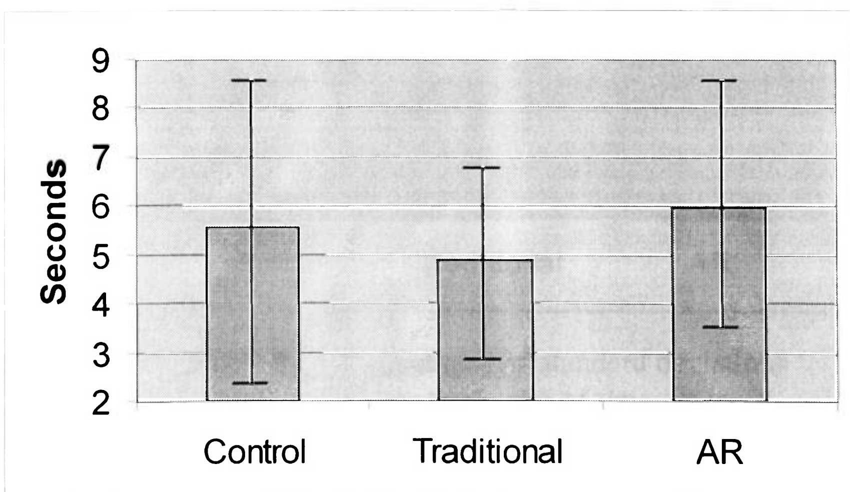

Figure 11. Graph depicting means and standard deviations for *time-on-task.*

Decision time.

The mean decision time (trial elapsed time minus time-on-task) for *no measurement device*, *traditional measurement device*, and *AR measurement device* were 13.41, 16.16, and 18.75 seconds, respectively. These means do not differ significantly using a one-way analysis of variance (ANOVA), $F(2,27) = 2.257$, $p = 0.124$. Thus, measurement device does not affect decision time during completion of this rivet installation task (Figure 12).

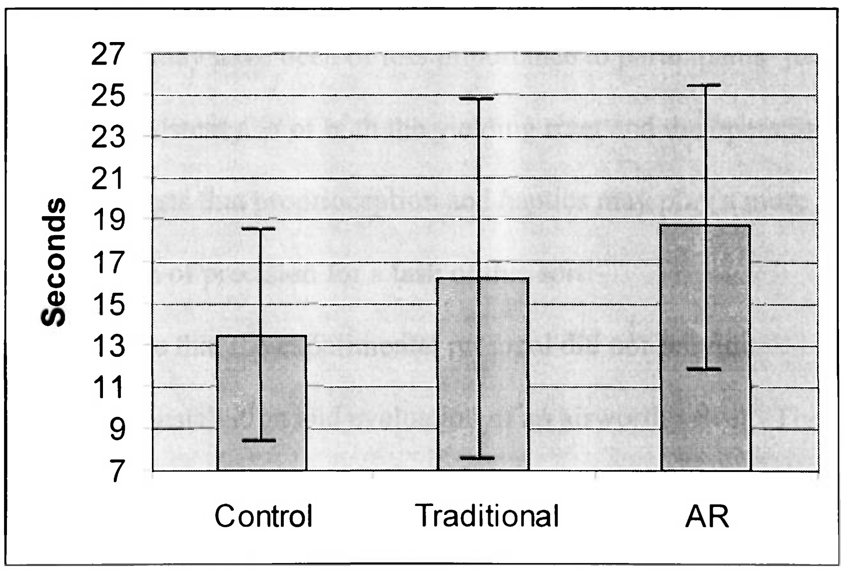

Figure 12. Graph depicting means and standard deviations for *decision time* (*elapsed time* exclusive of *time-on-task*).

DISCUSSION

With respect to measurement type, these data indicate that neither traditional nor AR measurement devices provide for better precision or rapidity in task completion. Although some general within subjects improvement for precision was indicated across trials, the absence of significant effect due to measurement type prevents any inference of causality.

A number of participants confided that the sensation of the rivet's yielding and the position of the rivet squeezer handles were powerful cues in judging task completion. By these assertions, the knowledge of results information provided by the various levels of the independent variable may have been of less importance to participants' judgement of rivet quality than the consistent *feel* of both the yielding rivet and the operation of the installation tool. This suggests that proprioception and haptics may play a more significant role in evaluation of precision for a task of this sort.

It is important to note that the experimental protocol did not provide comprehensive training for installation and evaluation of an airworthy rivet. The experimental task represented an elemental aspect of rivet installation; that of crushing a cylinder and evaluating the results. For purposes of minimizing participant workload and for streamlining the experimental task, the procedure relied on the installation tool's intrinsic qualities of self-alignment. Beyond a single lateral diameter measurement, the overall quality of the rivet installation was not considered.

While providing for a task that was simple for participants to grasp, this design may have also provided for a task that was exceptionally simple to perform. This may have been evidenced by the observed mean of three rivet installations (n=30) and 35.22 seconds time-on-task (n=21) needed to meet the training criterion of two consecutive nominal installations. Finally, the lack of significance for measurement device type may have been influence by the fact that the skill was more or less fully acquired by the time participants entered into trials.

RECOMMENDATIONS FOR FUTURE RESERCH

Question of modal dominance. The apparatus and method used for this study were robust to the extent that they permitted the efficient and reliable gathering of the data indicated by the research design. Although significance was not found for measurement device, this work has served to indicate a future path that may capitalize these results.

The rivet installation-based task design remains convenient for future consideration. The materials are cost effective and their characteristics are highly consistent. Future studies may make excellent use of a similar task while incorporating proprioceptive and haptic measures.

Observation during trials raised interest in the relationship between skill acquisition and the feel of the task. Relating back to the literature, this suggests an investigation of salience for knowledge of results versus knowledge of performance where measurement device is knowledge of results and haptics/proprioception represents knowledge of performance.

That this study sought to investigate what, if any, role augmented reality might play in facilitating skill acquisition and has, perhaps, assisted in the realization the recommendation for further investigation into the role of haptics. By compositing the virtual stimulus with the real-world experience of task performance, as opposed to an immersive virtual simulation, as in the knowledge transfer research of Kozack et al. (1993), the tactile qualities of the true task were conserved while elements of simulation in the form of knowledge of results were incorporated. This quality of and environment of mixed realities allowed the identification of potentially salient cue that would have been masked had the environment been immersive.

Opportunities for redesign. Removal of the installation component of the task would serve to isolate and permit better study of the visual qualities. The same apparatus could be employed to provide a set of finished items of known dimension for participant inspection. The experimental task would then be one of acquisition of visual inspection reliability.

Manipulation of the psychophysical qualities of the task could provide for better assurance of participant reliance on visual cues. The use of harder rivet alloys and lengthened installation tool lever arms would capitalize Webber's Law that holds: discriminabilty will decrease as force applied and magnitude of movement increase.

Removal or randomized confusion of the haptic qualities of the installation task, through redesign of the installation equipment, may also be possible. This could be accomplished through remote actuation of the installation tool such that both the proprioceptive and the haptic sense of the task are stripped of any predictable relationship to the actions of installation.

Although the experimental means fell within the experimental tolerance for a nominal rivet, there existed notable individual differences. This was especially true of the AR treatment group. By trial block, AR group installations tended to be consistent within a few thousandths of an inch. However, certain participants squeezed consistently oversized rivets while others were consistently undersized. The overwhelming majority of cases reported their rivets as "satisfactory" installations. In less frequent cases, a rejected oversized rivet would be followed by a more oversized "satisfactory" installation. It should be noted that this condition was found in all treatment groups and it is perhaps of greater interest that it occurred at all in the *traditional measurement device* group.

This may suggest that, while precision was achievable for most AR participants, accuracy remained elusive. It may be of interest to investigate whether a magnified view of the workpiece would mitigate much or any of the individual difference indicated in the present research.

As shown in the trial briefing script, (appendix A) prior to trial block commencement, the AR treatment group was not permitted to see a finished rivet relative to the AR stimulus. It may also be of interest to investigate the degree to which training with a nominal, oversized, and/or undersized rivets, prior to experimental trials, would serve to limit individual differences with respect to accuracy.

Trial elapsed time as a dependant measure offers insight with respect to generalization to industrial application (e.g., material benefit for deployment of an AR measurement device toward the realization of savings in person-hours). For behavioral study, the utility of this measure falls short.

This is evidenced in the obvious limitations found when attempting to use *trial elapsed means* less *time-on-task means* to evaluate decision time. Here, the task differences between treatment groups become substantial obstacles to making any meaningful inferences with respect to the processes taking place within the task. In particular, measures that provide for differences for inspection device and installation tool handling between treatment groups would realize greater utility.

CONCLUSIONS

The present research found no indication that measurement device type influences the acquisition skills needed to reliably accomplish a rivet installation task. Anecdotal findings suggest that, for this experimental task, haptic and proprioceptive cues may be of greater significance than visual cues in judgement of task completion. To better understand those qualities that are invariant to both training and operational tasks, future research may seek to account for these cues. The employment of dependant measures that allow for examination of between groups task differences and the use of apparatus that provides for psychophysical principles of discrimination may yield conclusive results.

References

Azuma, R.T. (1997). A survey of augmented reality. Presence: *Teleoperators and Vitual Environments*, 6(4), 355-385.

Bajura, M., Fuchs, H., & Ohbuchi, R. (1992). Merging virtual objects with the real world: seeing ultrasound imagery within the patient, *Procedings of SIGRAPH* (pp. 197-204). New York, NY: ACM.

Bullinger, H., Bauer, W., & Braun M. (1997). Virtual environments. In G. Salvendy, (Ed.), *Handbook of Human Factors and Ergonomics.* New York, NY: John Whiley & Sons.

Carr, K. (1995). In Carr, K., & England, R. (Eds.). *Simulated and virtual realities; elements of perception.* Bristol, PA: Taylor & Francis.

Carswell. C.M., & Wickens, C.D. (1996). Mixing and matching lower-level codes for object displays; evidence for two sources of proximity compatibility. *Human Factors,38,* 1-22.

Caudell T.P., & Mizell D.W. (1992). Augmented reality of head-up display technology to manual manufacturing processes. *Procedings of the Twenty-fifth Hawaii International Conference on System Sciences* (pp. 659-669). Los Alamitos, CA: IEEE Computer Society

Chung, K.H., Shewchuk, J.P., & Williges, R.C. (1999). An application of augmented reality to a thickness inspection. *Human Factors 9,* 331-342.

Department of Transportation Federal Aviation Administration. (1998). *AC 43.13-1B Acceptable Methods, Techniques, and Practices; Aircraft Inspection, Repair & Alteration.* Washington, D.C.: U.S. Government Printing Office.

Drascic, D., Grodski, J., Milgram, P., Ruffo, K., Wong, P., & Zhai, S. (1999). *ARGOS: A Display System for Augmenting Reality.* Available: http://gypsy.rose.utoronto.ca/people/david_dir/CHI93/CHI93.full.html. Toronto, Ontario: Ergonomics in Teleoperation and Control Laboratory, University of Toronto

Ellis, S.R., & Menges, B.M. (1997) Judgements of the distance to nearby virtual objects; interaction of viewing conditions and accommodative demand. *Presence 6(4),* 452-460.

Elvers, G. C., & Dolan, N. J. (1995). A comparison of the augmented bar display and the object display. *Ergonomics, 38*, 777-792.

Gentile, A.M. (1972). A working model of skill acqusition with application to learning. *Quest, 17,* 3-23.

Goodbody, S.J., & Wolpert, D.M. (1998). Temporal and amplitude generalization in motor learning. *Journal of Neuropsychology, 79,* 1825-1838.

Haniff, D. (1999) Augmented reality and computer-assisted learning. *Journal of Computer-Assisted Learning, 15,* 173-176.

Hays, R. T. & Vincenzi, D. A. (2000). Fleet Assessments of a Virtual Reality Training System. *Military Psychology 12 (3),* 161-186.

Heller, M. A., Calcaterra, J.A., Green, S.L., & Brown, L. (1999) Intersensory conflict between vision and touch: the response modality dominates when precise, attention-riveting judgment are required. *Perception & Psychophysics, 61 (7).* 1381-1398.

Kendrodle, M.W., & Carleton, L.G. (1992). Information feedback and the learning of multiple-degree-of-freedom activities. *Journal of Motor Behavior, 24,* 187-195.

Kijima, R., & Ojika, T. (1997). Transition between virtual environment and workstation environment with projective head mounted display. *Proceedings of IEEE 1997 Virtual Reality Annual International Symposium.* Los Alamitos, CA: IEEE Computer Society.

Kim, D., Richards, S.W., & Caudell, T.P. (1997). An optical tracker for augmented reality and wearable computers. *Proceedings of IEEE 1997 Virtual Reality Annual International Symposium.* Los Alamitos, CA: IEEE Computer Society.

Klinker, G., Strickler D., &. Reiners D. (1998). The use of reality models in augmented reality applications. In G. Goos, J. Hartmenis, & J. Van Leeuwen (Eds.). *3D Structure from Multiple Images of Large Scale Environments.* Berlin: Springer-Verlag

Kozack, J.J., Hancock, P.A., Arthur, E.J., & Chrysler, S.T. (1993). Transfer of training from virtual reality. *Ergonomics. 36* 777-784.

Kroemer, K.H.E., & Grandjean, E. (1997). *Fitting the Task to the Human fifth editiotion.; A Textbook of Occupational Ergonomics.* Bristol, PA: Taylor & Francis.

Lintern, G., (1991). An informational perspective on skill transfer in human-machine systems. *Human Factors 33,* 251-266.

Lintern, G., Roscoe, S., & Sivier, J.E. (1990). Display principles, control dynamics, and environmental factors in pilot training and transfer. *Human Factors 32 (3)*, 299-317.

Majoros A. E., & Boyle, E. (1997). Maintainability. In G. Salvendy (Ed.). *Handbook of Human Factors and Ergonomics.* New York, NY: John Whiley & Sons.

Melzer, E. J., & Moffit, K. (1997). *Head Mounted Displays; Design for the User.* New York, NY: McGraw Hill.

MIT Media Lab (1995). *ALIVE: Artificial Life Interactive Video Environment.* Available: http://alive.www.media.mit.edu/projects/alive/. Cambridge, MA: Massachusetts Institute of Technology.

Neumann U., & Majoros, A. (1998). Cognitive, performance, and systems issue for `augmented reality applications in manufacturing and maintenance. *Proceedings of the IEEE 1998 Virtual Reality Annual International Symposium.* Los Alamitos, CA: IEEE Computer Society.

Newell, K.M., & Carlton, M.J. (1987). Augmented information and the acquisition of isometric tasks. *Journal of Motor Behavior, 19,* 4-12.

Psotka, J. (1995). Immersive training systems; virtual reality and education and training. *Instructional Science 23,* 405-431.

Regan D, (1997). Perceptual motor skills and human motion analysis. In G. Salvendy, (Ed.). *Handbook of Human Factors and Ergonomics.* New York, NY: John Whiley & Sons.

Rolland, J.P., Biota, F.A., Barlow, T., & Kancheria, A. (1995). Quantification of adaptation to virtual-eye location in see-through head-mounted displays. *Proceedings of Virtual reality annual international symposium '95.* Los Alamitos, CA: IEEE Computer Society.

Schumann, H., Burtescu, S., & Siering, F. (1998). Applying augmented reality techniques in the field of interactive collaborative design. *Proceedings of SMILE'98; 3D Structure from Multiple Images of Large-Scale Environments. European Workshop.* Freiburg, Germany: 290-303.

Siebert, F. & Kühner, H. (1998). A vision based system controling the virtual tables camera. In F. Dai (Ed). *Virtual Reality for Industrial Applications.* Berlin: Springer-Verlag.

Swezey, R.W., & Llaneras R.E. (1997). Models in training and instruction. In G. Salvendy, (Ed.). *Handbook of Human Factors and Ergonomics.* New York, NY: John Whiley & Sons.

Todorov, T., Shadmehr, R., & Bizzi, E. (1997). Augmented feedback presented in a virtual environment accelerates learning of a difficult motor task. *Journal of Motor Behavior, 29,* 147-158.

Vander Linden, D.W.V., Cauraugh, J.H., & Greene T. A. (1993). The effect of frequesncy of kinetic feedback on learning an isometric force production task in nondisabled subjects. *Physical Therapy, 73,* 79-87.

Wickens, C.D., & Carswell, C.M. (1995). The proximity compatibility principle: its psychological foundation and relevance to display design. *Human Facors, 37,* 473-494.

Wise, J.A., & Sherwin, G.W. (1989, April). An empirical investigation of the effect of virtual collimated displays on visual performance. *Proceedings of the Fifth International Symposium on Aviation Psychology, Columbus, OH.* 743-748.

Appendix A

Participant Scripts

Training Script:

The experiment in which you are about to participate is designed to investigate new techniques associated with the installation of aircraft structural fasteners. During this experiment, you will install a series of standard aircraft rivets using a common rivet-squeezing tool.

I will now introduce each technique and the tools you will use to perform the task. We will begin the actual trial block after you have accurately installed two consecutive rivets on metal cards.

The equipment and tools that you will be trained to use today include:

A hydraulic vice

Metal cards preloaded with a rivet

A hand rivet squeezer tool

A measuring device (digital caliper)

Each metal card will be handed to you, you will place it in the hydraulic vice, position the card, use the hand squeezer tool to install the rivet and then measure each rivet to access its diameter.

Now we will begin the training session

Operation of the hydraulic vice:

In front of you is a hydraulic vice.

The vice is opened by firmly depressing the foot-pedal that is located to your right on the floor in front of you.

During the trial block, I will be sitting here (indicate experimenter's panel). I will be passing you individual metal cards containing a single rivet. TO prevent the rivet from falling out of the card., the head of the rivet will be at the top of the card and the tail will be pointing down. Please take the card from me by grasping the top of the card so that your fingertips curl over its top, capturing the head of the rivet. This way, the rivet cannot fall out of the card while you are handling it.

Place the metal card that I have handed you in the vice.

Position the card in the jaws of the vice so that round tail of the rivet is at the top of the card and is facing you. Notice that guides have been installed in the jaws of the vice. Position the card so that it rests against the jaw's left most guide. Continuing to hold the card with your fingers curled over the top and your fingertips holding the head of the rivet accomplishes two things. Fist, the rivet cannot fall out of the card when the vice is closed. Second, holding the card in this way will prevent your fingers from being pinched by the jaws of the vice.

The vice is closed by moving the lever to your left to its full upward position. The lever will automatically return to its original location.

Handing and application of the hand rivet squeezer;

After you have positioned the metal card, you will install a rivet using the hand rivet squeezer tool that is resting on the bench to your right. This tool has been modified with delicate switches that operate recording equipment. For this reason, you must use caution to avoid pressing the handles together while positioning the tool on the rivet and while setting it back onto the workbench. Please use caution to avoid striking the switches either on the jaws of the vice or on the workbench.

Also, use caution to avoid bumping the glass plate through which you are looking.

Hold the rivet-squeezing tool so that the movable arm is held in your right hand. You will use both hands to support the tool. Apply the rivet squeezer to the right-hand side of the card. Center the squeezing surfaces with the head and the tail of the rivet. The tool is designed to position itself onto the rivet once properly aligned. Install the rivet by maintaining the tool's alignment with the rivet head and tail while firmly pressing the handles together. So long as you maintain proper alignment, the installed rivet will be almost perfectly round.

Handing, application, and interpretation of the digital calipers for measurement of installed rivets along their lateral axis.

The diameter of the rivet must be measured in order to assure that it has been properly installed. For this portion of the experiment, you will do this by using of a pair of digital calipers. By gently closing the jaws of the calipers on the sides of the rivet tail, you can read its diameter on the caliper's digital display. Make use of the "flats" of the caliper jaws rather than the beveled points. The display indicates in decimal values of an inch, up to six inches.

Instruction on evaluation criteria of finished rivets for the tolerance of 0.230in to 0.250in.

For this experiment, the correct size of a finished rivet is any diameter between 0.230in and 0.250in. The ideal diameter is 0.240in. You may apply the squeezer tool as many times as you wish to meet the correct value. However, you must apply the measuring device after each squeeze.

Generic trial briefing (all treatments):

We will now proceed with the experimental portion of the study. During each trial your goal will be to do your best to produce, with as much precision as possible, a round finished rivet within the size range that you learned during training (0.230in – 0.250in). Time is a factor during the trials. Therefore, you should work as rapidly as possible and employ the least number of squeezes necessary to accomplish your goal.

Before each trial, you will be handed a card that has been preloaded with one rivet. Note that unlike the cards used during training, the faces of these cards are painted black. You will position the card in the vice just as you did during the training session.

Each experimental trial in this sequence will have a clear beginning and end. Trials begin upon movement of the lever to close the vice. Trials end upon reporting your perceived quality of the finished rivet. This is done through use of the "satisfactory" or "reject" buttons mounted in the box that is secured to the desk in front of you.

You will be instructed when to begin the first trial. When you have positioned the card and are ready to begin, move the lever on your left fully forward to both close the vice and to start the trial timer. Work as rapidly as possible while taking care to neither damage the switches on the squeezer nor strike the glass through which you are looking. Apply the squeezer just as you did during training.

No measurement device group:

Recall the image from your training of a correctly finished rivet. If the rivet that you have just installed appears smaller than the rivets that you recall from your training, continue to squeeze the rivet. When you are satisfied that the rivet that you have produced is of the same dimension as your correctly installed training rivets, indicate this by depressing the "satisfactory" button. If you feel that the finished rivet has exceeded its acceptable diameter, depress the reject button. This will stop the trial timer and illuminate a light that indicates your response. You may then open the vice and hand me the finished card.

There will be a brief pause while the trial data is recorded. You will then be handed another card. Please wait until your response light goes out before proceeding with the next trial.

Traditional measurement device group:

After each squeeze, make use of the digital calipers to measure the diameter of the rivet. If the rivet that you have just installed is smaller than 0.230in, continue to squeeze the rivet. When you are satisfied that the rivet that you have produced is larger in diameter than 0.230in but not greater than 0.250in, indicate this by depressing the "satisfactory" button. If you feel that the finished rivet has exceeded its acceptable diameter of 0.250in, depress the reject button. This will stop the trial timer and illuminate a light that indicates your response. You may then open the vice and hand me the finished card.

There will be a brief pause while the trial data is recorded. You will then be handed another card. Please wait until your response light goes out before proceeding with the next trial.

Augmented reality measurement device group:

Gently place your forehead against the orange forehead rest. Notice as you look through the glass that you can see the image of green segmented ring.

Are you able to clearly see a single segmented green ring and does it appear to be centered in the area of the glass plate? Does the forehead rest in any way restrict your vision?

The inside dimension of this ring corresponds to the minimum acceptable diameter of the finished rivet. The outside of the ring corresponds to the maximum acceptable diameter.

After each squeeze, gently place your forehead against the rest that is positioned just above the glass. Position your eyes so that the ring is centered on the rivet. If the rivet that you have just installed is smaller than the inside diameter of the ring, continue to squeeze the rivet. When you are satisfied that the rivet that you have produced has "touched" the inside of the ring but not exceeded the outside, indicate this by depressing the "satisfactory" button. If you feel that the finished rivet has exceeded its acceptable diameter, depress the reject button. This will stop the trial timer and illuminate a light that indicates your response. You may then open the vice and hand me the finished card.

There will be a brief pause while the trial data is recorded. You will then be handed another card. Please wait until your response light goes out before proceeding with the next trial.

Appendix B

Representative Score Sheet

Representative score sheet

Seq:	13	Prac to Crit:	2
Date:	8/12/00	TOT to Crit:	44.41
Time:	15:00		
Level:	3	Gender:	F
Block:	2	Age:	20

Trial	FD	TET	TOT	AF	PQ
1	0.236	21.67	5.29	1	S
2	0.233	20.63	5.91	1	S
3	0.239	18.90	4.59	1	S
4	0.241	20.03	4.50	1	S
5	0.235	18.95	3.88	1	S
6	0.235	19.27	3.83	1	S
7	0.237	18.20	4.13	1	S
8	0.242	20.99	3.97	1	S
9	0.241	20.17	3.91	1	S
10	0.243	23.33	4.22	1	S
11	0.242	19.34	5.71	1	S
12	0.244	26.39	4.02	1	S
13	0.232	34.99	7.73	2	S
14	0.241	18.33	4.37	1	S
15	0.237	18.57	3.87	1	S
16	0.238	32.58	9.27	2	S
17	0.242	20.31	4.19	1	S
18	0.244	18.53	3.87	1	S
19	0.237	19.31	3.99	1	S
20	0.230	19.88	4.35	1	S

Key to score sheet nomenclature, abbreviations, and codes:

Seq:	Position in trial block sequence (1-30)
Prac to Crit:	Number of rivets installed to meet training criterion
TOT to Crit:	Accumulated squeeze time to meet training criterion (seconds)
Level	Level of the Independent Variable (1 = Control; 2 = Traditional; 3 = AR)
Block	Trial block (1-10 for each level of the IV)

Key to trial data codes:

FD:	Finished diameter in inches
TET:	Trial elapsed time (seconds)
TOT:	Time-on-task (seconds)
AF:	Application frequency (number of squeeze events)
PQ:	Perceived quality (s = satisfactory, r = reject)