Medical Telementoring Using an Augmented Reality Transparent Display

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ABSTRACT

Background The goal of this study was to design and implement a novel surgical telementoring system called STAR (System for Telementoring with Augmented Reality) that uses a virtual transparent display to convey precise locations in the operating field to a trainee surgeon. This system was compared to a conventional system based on a telestrator for surgical instruction.

Methods A telementoring system was developed and evaluated in a study which used a 1 x 2 between-subjects design with telementoring system, i.e. STAR or Conventional, as the independent variable. The participants in the study were 20 pre-medical or medical students who had no prior experience with telementoring. Each participant completed a task of port placement and a task of abdominal incision under telementoring using either the STAR or the Conventional system. The metrics used to test performance when using the system were placement error, number of focus shifts, and time to task completion.

Results When compared to the Conventional system, participants using STAR completed the two tasks with less placement error (45% and 68%) and with fewer focus shifts (86% and 44%), but more slowly (19% for each task).

Conclusions Using STAR resulted in decreased annotation placement error, fewer focus shifts, but greater times to task completion. STAR placed virtual annotations directly onto the trainee surgeon's field of view of the operating field by conveying location with great accuracy; this technology helped to avoid shifts in focus, decreased depth perception, and enabled fine-tuning execution of the task to match telementored instruction, but led to greater times to task completion.

1 INTRODUCTION

2 Because many surgeons remain less well-trained outside their subspecialization,¹ some
3 surgeons may be less well prepared to treat trauma cases effectively in austere environments,
4 such as those occurring in the military. A broad range of expertise for optimal treatment is
5 required which is not readily available at the point of injury or at the required time.² Traumatic
6 injuries suffered in combat which require immediate care must be completed in forward
7 operating bases lacking direct access to a wide array of specialist surgeons. Similarly, general
8 surgeons in rural areas are disadvantaged when required to perform surgical procedures
9 requiring expertise beyond what is available at the local hospital. In such situations, transporting
10 the patient to a major medical facility may not be feasible. The prospect of using information
11 technology, computer graphics, and computer vision to provide remote instruction is a possible
12 solution. In this manuscript, we discuss our implemented surgical telementoring system.

13 Telementoring, the use of information technology to provide real-time, remote guidance
14 to a trainee surgeon from an expert mentor surgeon, can address these issues. Telementoring
15 has shown the following benefits. By introducing new surgical techniques to remotely located
16 trainees, telementoring has been used successfully to provide guidance to surgeons in the
17 completion of procedures which were initially unfamiliar to them,³ and by providing assistance
18 closer to the point of injury, transportation-related delays that can affect the patient adversely
19 can be avoided.⁴

20 Existing surgical telementoring systems rely on telestrators used by the mentor to
21 overlay graphic or textual annotations onto imagery of the surgical environment. These images
22 are displayed to the trainee typically on a nearby computer monitor. Budrionis et al. suggested
23 that telestration is a core feature of telementoring solutions and that a research gap exists
24 regarding the impact and details of telestration itself.⁵

1 The conventional telestrator-based approach has a substantial disadvantage; trainees
2 must shift focus repeatedly between the operating field and the telestrator. When a mentor is
3 co-located physically with the trainee, the mentor can use hands or surgical instruments to
4 indicate locations directly within the operating field. For example, hand gestures were used to
5 interact with MRI images in the operating room in our previous work.^{6,7} When using a telestrator,
6 however, focus shifting from the operating field to some other monitor (like a computer screen)
7 adds additional indirection. The trainee must look at the telestrator, understand the provided
8 guidance, then look back at the operating field and map the instructions mentally onto the real-
9 world scene.³ This indirection creates additional cognitive load, risking decreases in surgical
10 performance.

11 Recent research into surgical telementoring has emphasized the importance of
12 reevaluating the role of the telestrator-based approach. Ereso et al. developed a telementoring
13 system using a telestrator-based video connection with mentor-controlled pan/tilt functionality,
14 but most notably using a laser pointer that could be remote-controlled by the mentor to point
15 virtually at areas of interest directly on the operating field. Satisfaction surveys completed
16 afterward indicated that while the telestrator was unnecessary for several trainees, the ability of
17 the mentor to indicate areas directly in the trainee's field of view was useful.³ Other research
18 has focused on enhancing the ability of the mentor to demonstrate proper actions of the trainee.
19 Vera et al. implemented and validated an augmented reality telementoring (ART) platform,
20 which overlaid a live view of the surgical instruments manipulated by a remotely located mentor
21 onto the laparoscopic monitor viewed by a trainee to conduct a simulated laparoscopy. This
22 approach showed the effectiveness of overlaying mentor guidance directly onto the trainee's
23 view of the operating field; because the trainee normally views the operating field through the
24 laparoscopic monitor, there was no active focus shifting.⁸ Another approach to augmented
25 reality telementoring called Virtual Interactive Presence and Augmented Reality (VIPAR) used a
26 set of binocular videoscopes through which both trainee and mentor could view the operating

1 field augmented with mentor-provided overlays. This system allowed a mentor to “see what the
2 local surgeon sees,” and was used successfully while performing a carotid endarterectomy and
3 pterional craniotomy; a major disadvantage, however, was that the bulky eyewear of the
4 apparatus forced the trainee to operate from a fixed, rigid location.⁹ Augestad et al. reviewed
5 recently the state of surgical telementoring research and determined that the impact of
6 telementoring on surgical training has improved over time, but emerging technologies related to
7 portable and mobile devices, such as tablets or other smaller, less cumbersome devices,
8 remain an open area of research.¹⁰

9 We designed and developed a surgical telementoring system called STAR (System for
10 Telementoring with Augmented Reality) based on an augmented reality display that simulates a
11 transparent effect.¹¹ This work was begun by Loescher et al., who investigated an augmented
12 reality approach to surgical telementoring, displaying annotations on a tablet suspended
13 between the trainee and the operating field.¹² But, instead of displaying mentor annotations on a
14 screen that was located separate from the operating area, the current STAR system places
15 annotations directly into the field of view of the trainee surgeon (Figure 1, top). As a result, the
16 trainee surgeon does not need to shift eye focus to get information from a remote mentor. In
17 addition, because the annotations are overlaid directly onto the trainee’s view of the operating
18 area, the trainee does not need to remap annotations mentally to the current context. This
19 system was developed using formative feedback provided by surgeons during an advanced
20 trauma operative management course (ATOM) (Figure 1, bottom). The purpose of the current
21 study was to evaluate the effectiveness of the novel surgical telementoring system, STAR, when
22 compared to the conventional telestrator approach.

23 SYSTEM DESCRIPTION

24 STAR provides the trainee with an augmented “window” through which the trainee views
25 the operating field while completing the operation. The following discussion describes the

1 design and architecture of STAR and the subsystems (the trainee subsystem and the mentor
2 subsystem) through which the trainee and mentor interact to complete a telementored
3 operation.

4 Figure 1 shows the trainee subsystem. The tablet captures and displays live video of the
5 operating field using its camera. When the trainee surgeon conducts a telementored operation,
6 this trainee tablet is held in between the operating field and the trainee's head by a manipulator.
7 This position allows the trainee to view the operating field and his or her hands by looking
8 "through" the tablet while conducting a telementored procedure. The trainee tablet is networked
9 wirelessly with a remote mentor subsystem. As the trainee subsystem captures live video of the
10 operating field, it transmits video frames to the mentor subsystem.

11 The mentor uses a tablet subsystem to view the operating field remotely and to place
12 graphic annotations. The mentor subsystem displays the live video provided by the trainee
13 subsystem, allowing the mentor to view the operating area remotely. The mentor subsystem has
14 a touch-based user interface, which lets the mentor create, delete, and modify annotations
15 overlaid onto an image frame from the trainee subsystem. Supported types of annotations
16 include points, lines, loops, semi-transparent icons of surgical instruments and hand gestures,
17 and text labels. Using multi-touch controls, these annotations can be rescaled, rotated, and
18 repositioned.

19 Once annotations are created, the mentor subsystem transmits them to the trainee
20 subsystem. When the trainee subsystem receives the annotations, with a delay of only about
21 100 ms, the annotations are displayed on screen directly in the trainee's view of the operating
22 area. By means of computer vision algorithms, these annotations are anchored to relevant
23 areas of the operating field, avoiding drift as the trainee tablet is repositioned or as the operating
24 field changes.

METHODS

Our study was conducted with 17 pre-medical and 3 medical students at Purdue University. Each participant completed two simulated tasks: placement of an incision for port placement, and an abdominal incision. In each task, participants acted as a trainee in a telementoring scenario with a simulated mentor providing incremental graphic annotations as the participant completed each stage of the task. Ten students used the STAR surgical telementoring system, while the other ten students used a conventional, telestrator-based system. For each task, we measured placement error, the number of focus shifts, and completion time.

Participants

Twenty students (ages 18-26) were recruited from the pre-medical and medical programs at Purdue University. No students had prior experience with either STAR or surgical telementoring in general. The study was approved by the Purdue University Institutional Review Board, and written participant consent was acquired prior to beginning the experiment.

STAR Condition

For the STAR condition, participants completed each task while using the STAR trainee subsystem. To ensure consistency, a simulated mentor controlled by the experimenters was used to provide annotations to participants. All annotations used during the experiment were pre-generated, and as each stage of each task was completed, the simulated mentor provided the annotation demonstrating the next step. Each annotation was sent to the trainee subsystem, where it was visible on screen for the participant to follow.

Conventional condition

For the Conventional condition, a simulated telestrator interface was developed. Before the experiment, reference images of the operating field were captured from the point of view of the trainee. These images were displayed on a 46-inch LCD monitor and placed on the other side of the patient simulator visible to the participant. Images were advanced sequentially using a keyboard user interface.

Tasks

Participants used either STAR or the conventional telestrator-based system (described above) to complete two telementored tasks. Participants completed each task by interacting with a patient simulator (developed in-house) placed on a table.

Port Placement

The first task evaluated how well a trainee can find locations in the human body for the purpose of surgical port placement (Figure 2, top). These locations were indicated via a simulated mentor, and each trainee was required to assign physical identifiers to these regions using small adhesives. Participants were provided small circular adhesives (6.4 mm in diameter) to place over the patient simulator, representing the location of surgical ports. Participants were given a verbal description of the task and instructed to complete it quickly but accurately. During the task, the mentor would annotate seven locations one at a time on an image of the neck of the patient simulator. Participants were tasked with placing an adhesive on each corresponding physical location on the patient simulator.

For each participant, this task was repeated for a total of three trials. To avoid task memorization, subsequent trials displayed differing sequences and positions of circle annotations. After each trial, any placed adhesives were removed.

1 For the STAR condition, participants viewed the mentor annotations using the STAR
2 trainee tablet. For all participants, the trainee tablet was positioned at an identical location,
3 pointing the tablet camera at the neck area of the patient simulator. Annotations appeared
4 overlaid onto the live video (Figure 2, bottom). After each trial, an image was captured from the
5 camera on the trainee tablet to record the placed locations of the adhesives from a reference
6 position.

7 For the Conventional condition, participants received mentor guidance by viewing the
8 nearby LCD monitor. The monitor displayed a reference image of the neck area of the patient
9 simulator, overlaid with annotations displayed one at a time. After completing each trial of this
10 task, we recorded an image of the adhesives as placed by the participant.

11 12 Abdominal Incision Task

13 The second task consisted of performing an abdominal incision and exposure using the
14 same patient simulator (developed in-house) described earlier (Figure 3). Participants were also
15 provided with a scalpel, retractor, surgical scissors, four clamps, and a felt-tipped marker. Prior
16 to the task, each participant was shown a 4 min video demonstrating the task to be completed.
17 In the task, the surgeon used a scalpel and scissors to make an incision and used the retractor
18 and clamps to spread the linea alba. Before each incision and each use of the retractor or a
19 clamps, the trainee drew either an incision line or a circle at the point of contact using the felt-
20 tipped marker.

21 Next, the surgical instruments were placed on a tray near the incision simulator, and the
22 participant was tasked with repeating the previously-viewed procedure on the actual incision
23 simulator, step by step as mentor-provided annotations were displayed to the participant. This
24 procedure was repeated for a total of two trials by each participant.

25 For the STAR condition, participants viewed the simulated operating field by viewing the
26 trainee tablet screen held in a fixed pose over the abdominal area of the incision simulator. As

the participant completed each step of the procedure, pre-generated annotations were transmitted by the simulated mentor to the trainee tablet and displayed. These annotations showed the location of the incision and surgical instruments. For the Conventional condition, participants received mentor guidance by looking at the nearby LCD monitor, which displayed reference images of the incision simulator overlaid with annotations displayed one at a time.

Post-experiment

After completing all trials of each task under either the STAR condition or the Conventional condition, participants were asked to fill out a form indicating their age and their current year in their pre-med or medical studies. Participants received \$10 as compensation for their participation.

Study Design

Due to the specific repeated nature of each task (especially the abdominal incision task), we used a between-subjects study design. The type of surgical telementoring system was the independent factor; each participant used either the Conventional system or STAR. The pre-medical and medical population was combined, because their knowledge of the procedure was the same (no previous experience).

Dependent variables

For this study, the dependent variables were placement error, the number of focus shifts, and the time for completion of the task.

Placement Error. To determine the accuracy of surgical tool placement or incisions made, we measured the distance between marked locations in the image provided to the participants as guidance and the actual locations marked by participants during each trial. The marked

locations included the locations of adhesives, surgical instruments, and incision lines made during the task. This distance was the placement error measured in pixels on images captured from the same position relative to the operating field.

Focus shifts: We measured the number of times a participant shifted focus while completing a single trial. A focus shift was defined as a period of time when the participant was not looking directly at the operating field.

Task completion time: For each trial, we recorded the time for completion of the task, starting when a verbal indication was given to start and ending when the participant had completed the requested task and was no longer touching either the patient simulator or any attached surgical instruments.

Data Collection

To allow counting the focus shifts, participants wore a Google Glass head-mounted display (created by Google, Menlo Park, California) while completing each trial. The on-board camera on the Google Glass captured a video recording of the head movements of the participants. After the experiment, we analyzed these recordings and counted the focus shifts.

To measure placement error, images were recorded of the operating field for each task and overlaid onto reference images taken previously and used when generating the annotations. An automatic process was used to correspond the images to compensate for minor variation in the position of either the tablet or the patient simulator. After the images were overlaid, pixel distances were recorded between marked locations in the reference images and in the experimental images.

Statistical Analysis

For all the metrics measured, we wanted to compare two sampled populations based on the tested conditions for telementoring systems: a conventional approach and STAR. The responses used were the average of each metric for the 10 subjects in each condition; in the first task, each subject performed the placement task 3 times giving a total of 30 samples per condition. In the second task, the subjects performed the abdominal incision twice resulting in 20 samples for each condition. The first diagnostic to compare the populations was to check the normality assumption, using the Shapiro-Wilks test; when the test provided results pointing to non-normality of the collected data for a given metric, the non-parametric test Wilcoxon sign-rank was used to compare the medians and spreads of the responses from both conditions. In the cases where the Shapiro-Wilks test supported the normality assumption, a t-test was conducted using Satterthwaite condition for non-equal variance. Continuous data were summarized for the results section as mean (μ) $\pm$ SD (σ_x) for normally distributed data, or as median $\pm$ IQR values for data not normally distributed.

RESULTS

Placement Error

For the task of port placement, placement error for participants using STAR (Median = 23.73 px, IQR = 13.28 px) and the Conventional system (Median = 57.55 px, IQR = 32.80 px) was different ($P < 0.001$) with a median improvement of 33.8 px, representing a 59% decrease. Likewise, there was a 68% improvement ($P < 0.001$) decreasing 49.5 px in average the placement error for the abdominal incision task, from the Conventional system ($\mu = 72.6$ px, $\sigma_x = 16.9$ px) to STAR ($\mu = 23.1$ px, $\sigma_x = 8.4$ px).

Focus Shifts

For the port placement task, the number of focus shifts for participants using STAR (Median = 0, IQR = 0.5) was less ($P < 0.0001$) than for participants using the Conventional system (Median 13, IQR = 3.75). For the abdominal incision task, the number of focus shifts for participants using STAR ($\mu = 11.61$, $\sigma_x = 10.46$) was also significantly less ($P = 0.003$) than for participants using the Conventional system ($\mu = 20.68$, $\sigma_x = 5.78$).

Task Completion Time

For the port placement task, participants completed the task more slowly ($P = 0.0003$) when using STAR ($\mu = 48.0$ s, $\sigma_x = 15.5$ s) than when using the Conventional system ($\mu = 40.4$ s, $\sigma_x = 16.6$ s).

For the abdominal incision task, no statistically significant difference was found ($P = 0.165$) between the times to task completion for participants using STAR ($\mu = 274.9$ s, $\sigma_x = 86.9$ s) and for participants using the Conventional system ($\mu = 231.1$ s, $\sigma_x = 63.4$ s). Both task completion times (port placement and abdominal incision) were normally distributed.

DISCUSSION

Placement Error: In each task, participants using STAR completed the task with significantly less placement error than participants using the Conventional system. One likely cause for the decrease in placement error is the direct overlay of annotations onto the operating field. When using STAR, trainees avoided the cognitive load involved in looking at a separate image of the operating field, interpreting it, and mapping the separate instructions onto the actual operating field.

Operations rely on a sequence of steps, each enacted on a previously altered operating field. When using static imagery for telementoring, trainees using a conventional system rely on

1 relative estimates of location based on their own prior actions, which can lead to accumulation
2 of error. For example, a participant placing an adhesive at an incorrect location may, when
3 shown a later port location, place the later adhesive in relation to the previous adhesive location
4 rather than an absolute position relative to the structures of the operating field. In contrast, live
5 feedback using STAR allowed for absolute reference points for guiding trainee actions, thereby
6 limiting accumulation of error.

7 It should be noted that, during the port placement task, some of the adhesives were
8 placed far from the location indicated by the annotation, even in the STAR condition (Figure 2,
9 top). Several participants reported difficulty in manipulating the adhesives with their fingers and
10 sticking them to the correct surface, which was a limitation of this task, possibly contributing to
11 the large variances in the data.

12
13 **Focus Shifts:** For each task, participants shifted focus away from the operating field much less
14 often when using STAR than when using the Conventional system. This finding was expected,
15 because the Conventional system requires the trainee to look away from the operating field to
16 see the mentor instruction to complete each task. In contrast, STAR placed annotations directly
17 in the trainee field of view overlaid onto the operating field, meaning no focus shifts were
18 necessary for the trainee to complete the tasks successfully (Figures 1 and 2). In fact, for each
19 task, there were several trials in the 10 subjects tested (6 trials for the port placement task, and
20 20 trials for the abdominal incision task), all completed while using STAR, where no focus shifts
21 were made.

22 In two cases, participants using STAR moved their heads routinely to look under the
23 tablet after viewing the annotations displayed on the tablet. A third participant using STAR
24 behaved similarly only when using the scalpel during the abdominal incision task. One possible
25 cause for this movement might have been due to a lack of training or familiarity with STAR,
26 causing participants to revert to a more familiar approach of regarding the tablet as a reference

screen rather than as a virtual window. Another cause could be the lack of depth perception on the tablet display, which decreases hand-eye coordination during higher-risk actions such as an incision.

Task Completion Time: Participants using STAR completed tasks slightly more slowly than when using the conventional system. This slowdown may be secondary to the decrease in placement error noted in participants using STAR. When using the Conventional system, participants lacked live feedback to evaluate how their current placement of surgical instruments correlated with the requested mentor instruction. As a result, these participants simply completed each stage of a task relying on an initial estimate of the correct placement. In contrast, participants using STAR had the benefit of real-time annotations being overlaid directly onto their view of the operating area as they completed the task.

Frequently, participants using STAR used a searching or hunting movement with their hands to complete the task. These trainees would place their hands or surgical instruments initially into the tablet's field of view at an initial estimated location, then correct the position slowly until the surgical instrument aligned with the provided overlay.

Other contributing factors may include a decreased level of hand-eye coordination in the current prototype system. One cause could be latency in the display of the operating field by the tablet. There is some delay (approximately 100 ms) between when the tablet camera captures a video frame and when the video frame is available in memory. In addition, the single camera of the STAR system provides only a two-dimensional view of the operating field to the trainee, which limits the depth perception of the trainee. In addition, when the trainee views the operating field through the tablet, the image is from the camera's perspective and not the trainee's perspective. As a result, the hands and the surgical instruments of the trainee appear unexpectedly magnified when viewing them through the tablet.

1 **Current Limitations and Future Research**

2 The main limitation of STAR is that the trainee subsystem is not truly a transparent
3 display; instead, it creates the impression of a transparent display by displaying a live video on
4 the trainee tablet screen. The tablet displays only a single image of the operating field from a
5 single camera on the tablet, which affects the trainee's depth perception. Displaying a 3D view
6 visible with special eyewear is a possible solution, as is using custom-made displays that
7 simulate a 3D effect for a limited field of view,¹³ though such hardware would currently require a
8 bulky apparatus to be worn by the trainee. There is also a short latency of about 100 ms in the
9 video feed, both in displaying captured video frames to the trainee and in transmitting them to a
10 mentor. Finally, because of the difference between the position of the camera of the tablet and
11 the position of the trainee's eyes, the video as captured by the trainee tablet may not always be
12 from the correct perspective of the trainee; this may cause minor mismatches between the
13 trainee's view of the operating field inside the tablet "window," and the trainee's real-world view
14 of the surrounding area. Future research will investigate computer vision and 3D reconstruction
15 techniques to detect the head position of the trainee and automatically correct for this, achieving
16 a true "transparent display" effect.

17 Compared to other telementoring system using virtual reality haptic controlled
18 instruments,¹⁴ or those using servos for controlling cameras and/or laser pointers to indicate
19 specific regions,³ the proposed system enables richer and more realistic annotations, it is
20 versatile, mobile and cheaper than the existing ones.

21 **CONCLUSION**

22 This study evaluated the ability of a tablet-based virtual transparent display surgical
23 telementoring system (STAR) to facilitate accurate performance of surgical tasks by a trainee
24 when guided under remote telementoring. Participants using the STAR technology completed
25 tasks with less error and fewer focus shifts. Even though participants using STAR completed the

1 surgical tasks slightly more slowly, the decreases in placement error suggest that surgical
2 telementoring systems that provide guidance directly onto the field of view of the trainee can
3 improve surgical performance.

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Legends

Figure 1: Top: The trainee subsystem for STAR. An incision line annotation (dark blue line) created by a remote mentor is displayed on the tablet's screen. Bottom: A prototype of the STAR trainee subsystem being tested by a trainee surgeon during an advanced trauma operative management course.

Figure 2: Top: The port placement task for the STAR condition. Bottom: Screenshot captured from the trainee tablet during the port placement task. Mentor-provided annotations (blue circles) indicate locations for the trainee to mark (green adhesives).

Figure 3: The abdominal incision task for the STAR condition. Annotations (blue circles and transparent clamp icons) show where the trainee should place clamps.