Medical telementoring using an augmented reality transparent display

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Background. *The goal of this study was to design and implement a novel surgical telementoring system called the System for Telementoring with Augmented Reality (STAR) that uses a virtual transparent display to convey precise locations in the operating field to a trainee surgeon. This system was compared with 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 × 2 between-subjects design with telementoring system, that is, STAR or conventional, as the independent variable. The participants in the study were 20 premedical 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 with the conventional system, participants using STAR completed the 2 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. (Surgery 2016;159:1646-53.)*

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

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

Existing surgical telementoring systems rely on telestrators used by the mentor to overlay graphic

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or textual annotations onto imagery of the surgical environment. These images are displayed to the trainee typically on a nearby computer monitor. Budrionis et al[5] suggested that telestration is a core feature of telementoring solutions and that a research gap exists regarding the impact and details of telestration itself.

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

Recent research into surgical telementoring has emphasized the importance of reevaluating the role of the telestrator-based approach. Ereso et al[2] developed a telementoring system using a telestrator-based video connection with mentor-controlled pan/tilt functionality, but most notably using a laser pointer that the mentor could control remotely to point virtually at areas of interest directly on the operating field. Satisfaction surveys completed afterward indicated that although the telestrator was unnecessary for several trainees, the ability of the mentor to indicate areas directly in the trainee's field of view was useful.[3] Other research has focused on enhancing the ability of the mentor to demonstrate proper actions of the trainee. Vera et al[8] implemented and validated an augmented reality telementoring platform, which overlaid a live view of the surgical instruments manipulated by a remotely located mentor onto the laparoscopic monitor viewed by a trainee to conduct a simulated laparoscopy. This approach showed the effectiveness of overlaying mentor guidance directly onto the trainee's view of the operating field; because the trainee normally views the operating field through the laparoscopic monitor, there was no active focus shifting.[8] Another approach to augmented reality telementoring called Virtual Interactive Presence and Augmented Reality used a set of binocular videoscopes through which both trainee and mentor could view the operating field augmented with mentor-provided overlays. This system allowed a mentor to "see what the local surgeon sees," and was used successfully while performing a carotid endarterectomy and pterional craniotomy; a major disadvantage, however, was that the bulky eyewear of the apparatus forced the trainee to operate from a fixed, rigid location.[9] Augestad et al[10] reviewed recently the state of surgical telementoring research and determined that the impact of telementoring on surgical training has improved over time, but emerging technologies related to portable and mobile devices, such as tablets or other smaller, less cumbersome devices, remain an open area of research.

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

SYSTEM DESCRIPTION

STAR provides the trainee with an augmented "window" through which the trainee views the operating field while completing the operation. The following discussion describes the design and architecture of STAR and the subsystems (the trainee subsystem and the mentor subsystem) through which the trainee and mentor interact to complete a telementored operation.

Fig 1 shows the trainee subsystem. The tablet captures and displays live video of the operating field using its camera. When the trainee surgeon conducts a telementored operation, this trainee

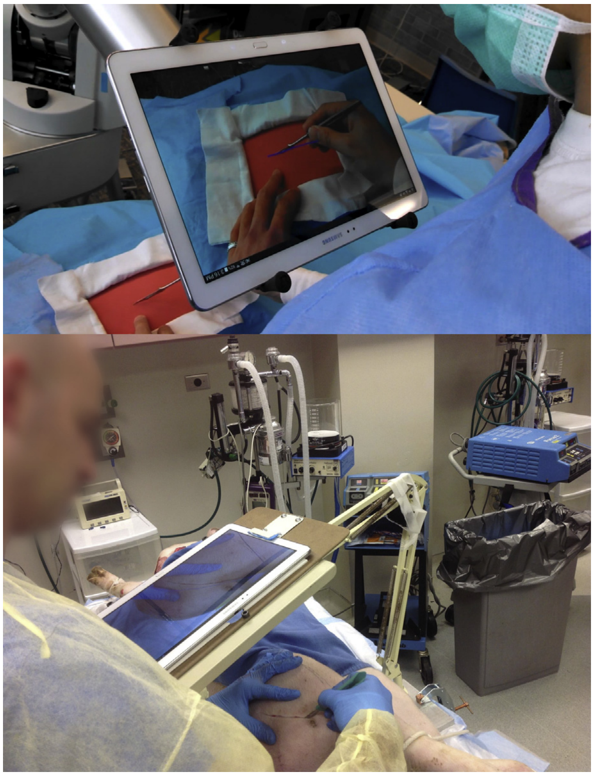

Fig 1. *Top*, The trainee subsystem for the system for telementoring with augmented reality (STAR). An incision line annotation (*dark blue line*) created by a remote mentor is displayed on the tablet's screen. *Bottom*, A prototype of the STAR trainee subsystem being tested by a trainee surgeon during an advanced trauma operative management course. (Color illustration of figure is available online.)

tablet is held in between the operating field and the trainee's head by a manipulator. This position allows the trainee to view the operating field and his or her hands by looking "through" the tablet while conducting a telementored procedure. The trainee tablet is networked wirelessly with a remote mentor subsystem. As the trainee subsystem captures live video of the operating field, it transmits video frames to the mentor subsystem.

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

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

METHODS

Our study was conducted with 17 premedical and 3 medical students at Purdue University. Each participant completed 2 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, and the other 10 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 premedical 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 before 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 pregenerated, 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.

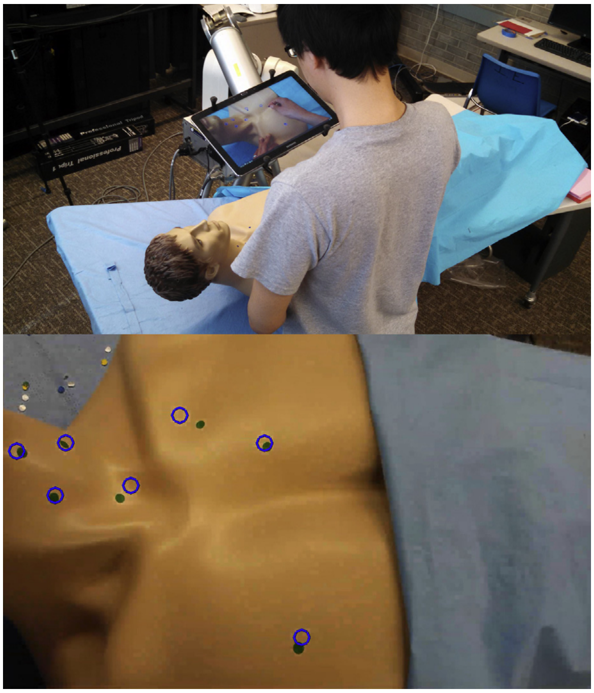

Fig 2. *Top*, The port placement task for the system for telementoring with augmented reality (STAR) condition. *Bottom*, Screenshot captured from the trainee tablet during the port placement task. Mentor-provided annotations (*blue circles*) indicate locations for the trainee to mark (*green adhesives*). (Color illustration of figure is available online.)

Tasks. Participants used either STAR or the conventional telestrator-based system (as described) to complete 2 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 (Fig 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 7 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 3 trials. To avoid task memorization, subsequent trials displayed differing

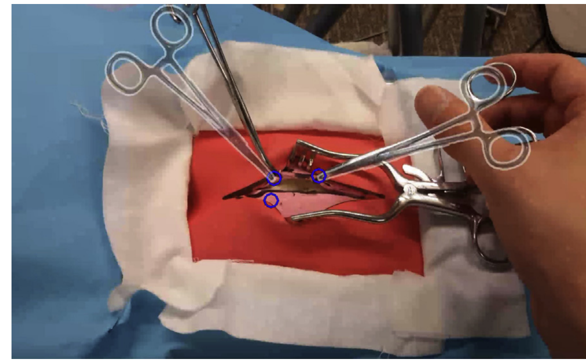

Fig 3. The abdominal incision task for the system for telementoring with augmented reality (STAR) condition. Annotations (*blue circles* and *transparent clamp icons*) show where the trainee should place the clamps. (Color illustration of figure is available online.)

sequences and positions of circle annotations. After each trial, any placed adhesives were removed.

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

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

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

Next, the surgical instruments were placed on a tray near the incision simulator, and the participant was tasked with repeating the previously viewed procedure on the actual incision simulator, step by step as mentor-provided annotations were displayed to the participant. This procedure was repeated for a total of 2 trials by each participant.

For the STAR condition, participants viewed the simulated operating field by viewing the 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, pregenerated 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.

After the 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 premedical or medical studies. Participants received $10 as compensation for their participation.

Study design. Owing 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 premedical 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, CA) 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 2 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 nonparametric test Wilcox 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 nonequal variance. Continuous data were summarized for the results section as mean (μ) ± standard deviation (σ_x) for normally distributed data, or as median ± interquartile range (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; IQR, 13.28 px) and the conventional system (median, 57.55; IQR, 32.80 px) was different ($P < .001$) with a median improvement of 33.8 px, representing a 59% decrease. Likewise, there was a 68% improvement ($P < .001$) decreasing 49.5 px in average the placement error for the abdominal incision task, from the conventional system (μ, 72.6; σ_x, 16.9 px) to STAR (μ, 23.1; σ_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 ($P < .0001$) 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 (μ, 11.61; σ_x, 10.46) was also less ($P = .003$) than for participants using the conventional system (μ, 20.68; σ_x, 5.78).

Task completion time. For the port placement task, participants completed the task more slowly ($P = .0003$) when using STAR (μ, 48.0 s; σ_x, 15.5 s) than when using the conventional system (μ, 40.4 s; σ_x, 16.6 s). For the abdominal incision task, no difference was found ($P = .165$) between the times to task completion for participants using STAR (μ, 274.9 s; σ_x, 86.9 s) and for participants using the conventional system (μ, 231.1 s; σ_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 relative estimates of location based on their own prior actions, which can lead to accumulation of error. For example, a participant placing an adhesive at an incorrect location may, when shown a later port location, place the later adhesive in relation to the previous adhesive location rather than an absolute position relative to the structures of the operating field. In contrast, live feedback using STAR allowed for absolute reference points for guiding trainee actions, thereby limiting accumulation of error.

During the port placement task, some of the adhesives were placed far from the location indicated by the annotation, even in the STAR condition (Fig 2, *top*). Several participants reported difficulty in manipulating the adhesives with their fingers and sticking them to the correct surface, which was a limitation of this task, possibly contributing to the large variances in the data.

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

In 2 cases, participants using STAR moved their heads routinely to look under the tablet after viewing the annotations displayed on the tablet. A third participant using STAR behaved similarly only when using the scalpel during the abdominal incision task. One possible cause for this movement might have been owing to a lack of training or familiarity with STAR, 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 2-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.

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

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

In conclusion, this study evaluated the ability of a tablet-based virtual transparent display surgical telementoring system (STAR) to facilitate accurate performance of surgical tasks by a trainee when guided under remote telementoring. Participants using the STAR technology completed tasks with fewer errors and fewer focus shifts. Even though participants using STAR completed the surgical tasks slightly more slowly, the decreases in placement error suggest that surgical telementoring systems that provide guidance directly onto the field of view of the trainee can improve surgical performance.

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REFERENCES

1. Borman KR, Vick LR, Biester TW, et al. Changing demographics of residents choosing fellowships: longterm data from the American Board of Surgery. J Am Coll Surg 2008;206:782-8.
2. Ereso AQ, Garcia P, Tseng E, et al. Live transference of surgical subspecialty skills using telerobotic proctoring to remote general surgeons. J Am Coll Surg 2010;211:400-11.
3. Treter S, Perrier N, Sosa JA, et al. Telementoring: a multi-institutional experience with the introduction of a novel surgical approach for adrenalectomy. Ann Surg Oncol 2013;20:2754-8.
4. Garcia P. Telemedicine for the battlefield: present and future technologies. Surgical Robotics 2011:33-68.
5. Budrionis A, Augestad M, Patel HR, et al. An evaluation framework for defining the contributions of telestration in surgical telementoring. Interact J Med Res 2013;2:e14.
6. Wachs JP, Stern HI, Edan Y, et al. A gesture-based tool for sterile browsing of radiology images. J Am Med Inform Assoc 2008;15:321-3.
7. Jacob MG, Wachs JP, Parker RA. Hand gesture-based sterile interface for the operating room using contextual cues for the navigation of radiological images. J Am Med Inform Assoc 2013;20:e183-6.

8. Vera AM, Russo M, Mohsin A, et al. Augmented reality telementoring (ART) platform: a randomized controlled trial to assess the efficacy of a new surgical education technology. Surg Endosc 2014;28:3467-72.
9. Shenai MB, Dillavou M, Shum C, et al. Virtual interactive presence and augmented reality (VIPAR) for remote surgical assistance. Neurosurgery 2010;68(1 Suppl Operative):200-7.
10. Augestad M, Bellika JG, Budrionis A, et al. Surgical telementoring in knowledge translation—clinical outcomes and educational benefits. Surg Innov 2010;20:273-81.
11. Andersen D, Popescu V, Cabrera ME, et al. Virtual annotations of the surgical field through an augmented reality transparent display. Vis Comput 2015:1-18.
12. Loescher T, Lee SY, Wachs JP. An augmented reality approach to surgical telementoring. Conf Proc IEEE Int Conf Syst Man Cybern 2014:2341–2346.
13. Maeda N, Sugimoto M. Pathfinder vision: tele-operation robot interface for supporting future prediction using stored past images. InACM SIGGRAPH 2014 Posters 2014 (p. 52). ACM.
14. Allen BF, Jordan B, Pannell W, Lewis C, Dutson E, Faloutsos P. Laparoscopic surgical robot for remote in vivo training. Adv Robot 2010;24:1679-94.