Surgical Telementoring Without Encumbrance

A Comparative Study of See-through Augmented Reality-based Approaches

Edgar Rojas-Muñoz, BS, Maria Eugenia Cabrera, MSc,* Daniel Andersen, MS,† Voicu Popescu, PhD,† Sherri Marley, BSN, RN,‡ Brian Mullis, MD,‡ Ben Zarzaur, MD, MPH, FACS,‡ and Juan Wachs, PhD**

Objective: This study investigates the benefits of a surgical telementoring system based on an augmented reality head-mounted display (ARHMD) that overlays surgical instructions directly onto the surgeon's view of the operating field, without workspace obstruction.

Summary Background Data: In conventional telestrator-based telementoring, the surgeon views annotations of the surgical field by shifting focus to a nearby monitor, which substantially increases cognitive load. As an alternative, tablets have been used between the surgeon and the patient to display instructions; however, tablets impose additional obstructions of surgeon's motions.

Methods: Twenty medical students performed anatomical marking (Task1) and abdominal incision (Task2) on a patient simulator, in 1 of 2 telementoring conditions: ARHMD and telestrator. The dependent variables were placement error, number of focus shifts, and completion time. Furthermore, workspace efficiency was quantified as the number and duration of potential surgeon-tablet collisions avoided by the ARHMD.

Results: The ARHMD condition yielded smaller placement errors (Task1: 45%, $P < 0.001$; Task2: 14%, $P = 0.01$), fewer focus shifts (Task1: 93%, $P < 0.001$; Task2: 88%, $P = 0.0039$), and longer completion times (Task1: 31%, $P < 0.001$; Task2: 24%, $P = 0.013$). Furthermore, the ARHMD avoided potential tablet collisions (4.8 for 3.2 seconds in Task1; 3.8 for 1.3 seconds in Task2).

Conclusion: The ARHMD system promises to improve accuracy and to eliminate focus shifts in surgical telementoring. Because ARHMD participants were able to refine their execution of instructions, task completion time increased. Unlike a tablet system, the ARHMD does not require modifying natural motions to avoid collisions.

Keywords: augmented reality, surgical telementoring, telemedicine, teleproctoring

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Surgical telementoring is a method to deliver specialized expertise to a mentee in scenarios where expertise is not readily available. For example, telementoring can allow a remote expert surgeon to convey specialized surgical expertise to a generalist surgeon in rural hospitals, in disaster-affected regions and in the battlefield. Furthermore, telementoring can disseminate surgical procedure innovations across the world.

Telestrators are the conventional approach for telementoring. A remote expert receives and annotates video imagery from a mentee's operating field. These annotations are sent back to the mentee where they are displayed on a nearby monitor. However, this approach requires the mentee to shift focus from the surgical field to the nearby monitor, and to memorize the annotations' positions to map them onto the patient's anatomy. This introduces additional cognitive load that can contribute to surgeon fatigue and error-prone performance.[1,2]

In previous work,[3] we leveraged augmented reality (AR) technology to improve surgical telementoring. With our system, dubbed the System for Telementoring with Augmented Reality (STAR), the mentee views the operating field through a tablet-based transparent display, which directly overlays mentor annotations onto the mentee's view of the surgical field (Fig. 1).

However, using a tablet at the mentee site possesses disadvantages. First, the tablet degrades the mentee's depth perception because of loss of stereopsis: binocular depth cues are not preserved

FIGURE 1. Top: STAR tablet-based setup. The tablet is held in place between the patient and the user with a mechanical bracket. Bottom: First-person view of an instruction received with the STAR tablet-based setup. The augmentation consists of 2D lines and images. The view of the camera is displayed on the device's screen.

From the *School of Industrial Engineering, Purdue University, West Lafayette, IN; †Department of Computer Science, Purdue University, West Lafayette, IN; and ‡School of Medicine, Indiana University, Indianapolis, IN.

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Reprints: Juan Wachs, PhD, Purdue University, 315 N. Grant Street, West Lafayette, IN 47907. E-mail: jpwachs@purdue.edu.

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because of the 2D nature of the tablet screen.[4] This can impair hand–eye coordination and increase hesitancy when performing precise tasks: mentees must guess how far their movements should go before reaching the destination, hindering task completion time. An example of this behavior can be found in our previous work.[5] Second, the tablet's position in range of the mentee's arms might impede the mentee's natural motion.

This article describes an enhancement of the STAR platform at the mentee site that preserves binocular depth cues by replacing the tablet with a see-through AR head-mounted display (ARHMD) worn by the mentee. 3D graphical annotations are overlaid onto the mentee's view of the surgical field, remaining anchored as the mentee moves. The ARHMD generates a different image for each eye, making the annotations perceivable at the correct depth relative to the patient's body. In addition, proper depth cues are preserved since see-through ARHMDs allow mentees to see the surgical field directly. Moreover, the ARHMD does not obstruct the surgeon's hands, as it is entirely self-contained on the head. We have conducted a user study that assesses the effectiveness of the new STAR platform in surgery. This study indicates that ARHMDs have great potential in surgical telementoring.

RELATED WORK

Telementoring has proved successful at developing surgeons' surgical skills when experienced mentors are not available,[6,7] and to avoid transportation-related delays of medical equipment and personnel.[8] Additional benefits are associated with telementoring in austere environments.[9] A review evaluating the tradeoffs between on-site mentoring and telementoring technologies revealed that each approach has its own challenges (ie, travel and time costs vs equipment cost and network issues).[10] Nonetheless, telementoring is an effective way to provide access to expert mentors and advanced surgical techniques that otherwise would be unavailable.

Telestrator-based technologies have demonstrated their usefulness in surgical telementoring.[11−13] These approaches rely on nearby monitors to show guidance sent by a remote expert. In recent years, preferences between 2D and 3D telestration have been researched. 2D telestration is more widely adopted because of its simplicity.[14,15] However, 2D annotations introduce occlusion issues and degrade binocular depth perception cues, hindering users' orientation in a 3D environment. Investigating 3D telestration, Ali et al[16] developed a video algorithm to translate instructions from mentors from 2D to 3D in a da Vinci surgical robot's console, and found that 3D robotic telestration is feasible and does not negatively influence performance in controlled tasks.

However, conventional telestrator-based approaches have a substantial disadvantage: mentees must shift focus repeatedly between the operating field and the monitor, which adds complexity and increases cognitive load.[17] This disadvantage can be mitigated by presenting information directly into users' field of view (FOV). AR has been used to accomplish this outside[18] and inside the surgical domain.[19] Although navigation-related AR applications exist for laparoscopic,[20] endoscopic,[21] and spinal surgery[22] procedures, AR systems remain unavailable and therefore untested in most surgical specialties.

State-of-the-art telementoring systems rely on tablet-based devices to augment the users' FOV.[3,23,24] However, this approach introduces additional encumbrance by placing the tablet in the surgeon's workspace. Head-mounted displays (HMDs) can address this drawback: while surgeons must wear a headset, workspace encumbrance is avoided. Systems reported in urology[25,26] allow mentors and mentees to exchange information, but either do not consider complex annotations or only provide 2D imagery, instead of 3D. Our work leverages the capacity of an ARHMD platform to display 3D annotations directly in the mentee's FOV, providing relevant instruction without focus shifts or workspace encumbrance.

SYSTEM DESCRIPTION

STAR is a surgical telementoring platform that displays annotations sent by a remote expert surgeon directly into a mentee's FOV. It is composed of 2 subsystems: the Mentor System, used by the mentors to deliver guidance to the mentees; and the Trainee System, which non-specialist/mentee surgeons use to receive visual instructions from the mentors. The current system allows the placement and anchoring of 3D imagery inside of the surgeon's unencumbered workspace. These annotations can be observed through the ARHMD's screen from any viewpoint (Fig. 2, *top*).

Consider the following example of how the STAR platform can be utilized. Dr. Harrison is a surgeon situated in an operating room who needs to perform a leg-fasciotomy on Mr. Smith, a patient suffering from compartment syndrome. However, Dr. Harrison has not received extensive training on this procedure and requires assistance. In this case, Dr. Harrison, wearing the ARHMD Trainee System, connects to the Mentor System, located at a Level 1 Trauma Facility where Dr. Grover, an attending in Orthopedic Trauma, is ready to provide support. The ARHMD broadcasts Dr. Harrison's FOV to Dr. Grover, who then uses the Mentor System to create surgical annotations (incision lines, surgical instruments, among others) in the live video sent by Dr. Harrison. These annotations are transmitted back to the ARHMD, which projects and anchors them in the right position over Mr. Smith's leg. Aided with these instructions, Dr. Harrison can successfully perform the leg-fasciotomy. Figure 2 (*bottom*) portrays an instruction as seen by the mentee wearing the ARHMD.

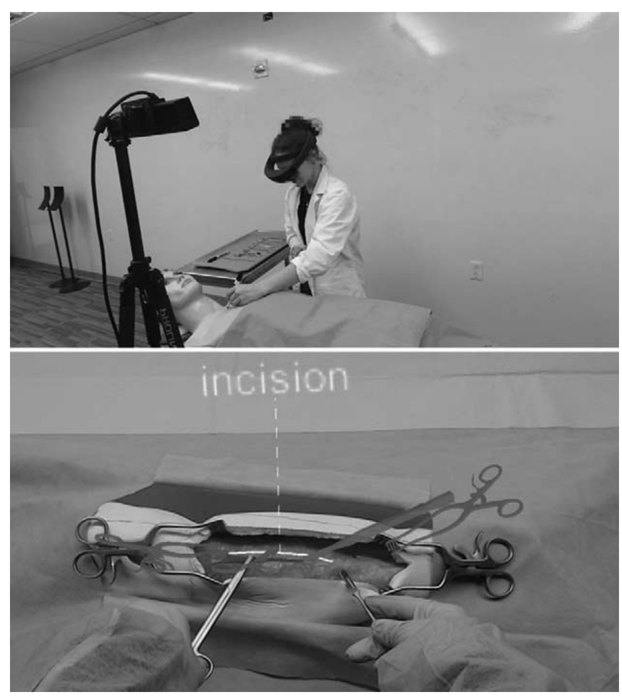

FIGURE 2. Top: STAR ARHMD setup. No additional artifacts are required except for the device worn by the user. Bottom: First-person view of an instruction received with the STAR ARHMD setup. The augmentation consists of 3D lines and 3D models visible only through the device's display.

METHODS

A user study was conducted at Eskenazi Hospital (Indianapolis, Indiana), where 20 medical students performed telementored tasks under 1 of 2 conditions: STAR ARHMD and conventional telestrator. The participants had to complete 2 different tasks on a patient simulator: an anatomical marker placement and a mock abdominal incision. These tasks depict core surgical skills present in most surgical procedures: landmark location and skin incision. These tasks are atomic building blocks for more complex procedures, and an initial evaluation of the system's effectiveness in these tasks would reveal insights for its application on more complex tasks. Moreover, effectiveness in these tasks is mandatory to ensure subsequent effectiveness in more complex scenarios.

Participant performance was recorded and analyzed using the following metrics: annotation placement error, task completion time, and number of focus shifts. The ARHMD was also compared against a tablet-based system[5]: by tracking the participants' limb motions and poses during the experiment, the number and duration of potential collisions avoided by the ARHMD system had a tablet device been there were calculated as a post-experiment metric. To maintain consistency among participants, preprogrammed annotations were used instead of live feedback from the Mentor System. The following subsections elaborate on the details of the experiment.

Participants

Twenty medical students (6 females, 14 males) ranging from 23- to 29 years old were recruited. Participants were in their second, third, or fourth year of medical school, and had no previous experience with surgical telementoring systems. The study was reviewed and approved by Indiana University Institutional Review Board (#1409037680), and written participant consent was acquired for each participant. Using medical students in the role of mentees has high ecological validity,[27] as telementoring is likely to be deployed to support medical students, new graduates, and other non-specialist surgeons. Moreover, because of the simplicity of the tasks, it was required that the participant's level of expertise was not that of an expert surgeon or a surgery resident: the objective was for the participants to rely in the telementored guidance instead of being able to complete the procedure alone. This configuration is an acceptable placeholder for a medic or a nonspecialist attempting to do a procedure for which they have little or no experience. Other studies have leveraged the medical student population in medical telementoring studies.[7,12,28,29]

Apparatus and Setting

Figure 3 presents a diagram of the experiment's setting. The experiment setup included: the patient simulator on the operating table, the participant acting as a mentee, an ARHMD (Microsoft HoloLens), and a nearby monitor located 60° to mentees' right. Surgical instruments to complete the tasks were located on a Mayo stand to the side of the operating table.

In the telestrator condition, participants looked at the nearby monitor to receive the instructions. The images shown on the telestrator were a top-down view of the region of interest on the patient simulator for each step of the procedure (Fig. 4, *top*). Participants in the STAR condition wore the ARHMD, which constructs a virtual representation of the space it is in, and enables the placement of virtual annotations in this representation, visible only to the user wearing the device. Participants followed a 3D replica of the instructions used in the telestrator condition, represented using 3D models of surgical instruments, 3D lines, and spheres (Fig. 4, *bottom*).

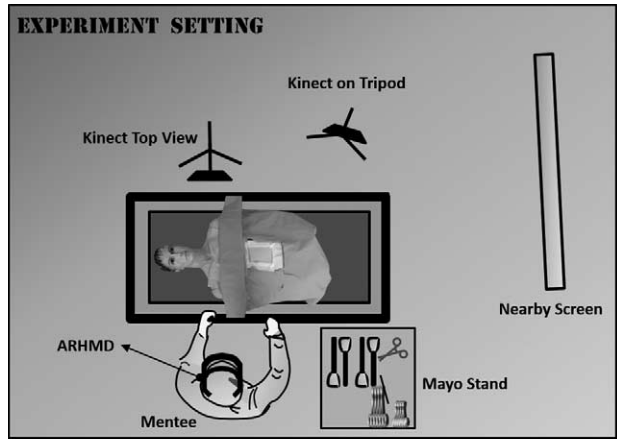

FIGURE 3. Experiment setting. For the telestrator condition, the participant used the nearby screen to retrieve the instructions. In the ARHMD condition, the instructions were shown via the device's screen.

FIGURE 4. Top: Participant performing a task using the telestrator-based condition. The instructions for the task are obtained by looking at a nearby screen. Bottom: Participant performing a task using the STAR ARHMD condition. Inset is the first-person view of the user wearing the ARHMD.

Data Collection

Two Microsoft Kinect devices were used to record videos of each participant's performance. One Kinect was placed fronto-parallel to the patient simulator and the participant, recording infrared, color, depth, and skeletal tracking data. The second Kinect was placed to capture a top-down view of the procedure, recording color, and audio. A calibration process was performed before the experiment, allowing a mapping between the ARHMD reference frame and the top-view Kinect. Time taken to complete each task was recorded using a stopwatch.

After performing both tasks, participants answered a questionnaire on their experience with the telementoring systems. The questionnaire (Fig. 5) contained 7 questions that evaluated each system in terms of communication efficiency, available functionalities, ease of use, and time required to complete the task. The questionnaire included a section for comments and suggestions.

Procedure

The experiment consisted of 2 tasks: an anatomical marker placement and a mock abdominal incision. The first task had 3 trials, whereas the second task had only 1 trial. Participants were briefed about both tasks before starting, and were encouraged to complete the tasks as quickly and accurately as possible.

Task 1: Marker Placement

Participants had to mark different locations on the simulator's body with a dry erase marker. Each trial included 7 circular-shaped annotations located around the patient's neck and chest. Each trial showed different locations to avoid recall.

Participant's age: __________ **Date:** __________

Participant's gender: ________ **Exp. Condition:** _______

Participant's career level (e.g. 3rd year resident): ________________________________

Post-Experiment Questionnaire

Please underline or circle the option that you identify with the most in each of the following questions.

The interaction method provided sufficient capabilities to successfully complete the procedure

Strongly Agree Agree Undecided Disagree Strongly Disagree

The mentor's instruction were easy to follow

Strongly Agree Agree Undecided Disagree Strongly Disagree

The interaction method was easy to use

Strongly Agree Agree Undecided Disagree Strongly Disagree

The information between mentor and trainee was efficiently exchanged

Strongly Agree Agree Undecided Disagree Strongly Disagree

The interaction method contributed to reduce the time taken to complete the procedure

Strongly Agree Agree Undecided Disagree Strongly Disagree

The interaction method generated frustration when trying to communicate with the mentor

Strongly Agree Agree Undecided Disagree Strongly Disagree

The interaction method impacted negatively the amount of time taken to complete the procedure

Strongly Agree Agree Undecided Disagree Strongly Disagree

Is there something that you think would be useful to add the interaction method used?

Do you have any other comments you would like to provide?

FIGURE 5. Post experiment questionnaire distributed to participants. The questionnaire assessed the telementoring system used by the participants with a five-level Likert scale and gave participants the option of providing additional comments regarding the system's features and usability.

Task 2: Abdominal Incision

Participants had to follow 16 instructions to cut through 2 simulated layers of skin and to spread the linea alba. Incisions on the skin layers had to be done without puncturing a balloon that simulated the stomach. Before the execution of each step, participants had to mark the locations/incision lines depicted in the instruction.

Experimental Design

A between-subject design was selected, randomly assigning participants to each of the 2 telementoring conditions. Condition was treated as an independent variable, whereas the performance metrics were treated as dependent variables. In addition, potential tablet collisions were calculated for the STAR condition. Finally, the questionnaire responses were used as a subjective metric to assess system usability.

Placement Error

The distance between the ground truth (represented by landmarks over the images) and the locations marked by the participants was measured. This distance was measured in centimeters: the depth position in the workspace of each annotation was retrieved with the Kinect and analyzed using a computer algorithm. For each annotation, the placement error is the average Euclidean distance between its ground truth and the mentee's marked location, in the 3D workspace. Averages per participant per trial were obtained for each task.

Task Completion Time

The time taken to complete each task was measured in seconds for each subject and task.

Focus Shifts

A focus shift was defined as a noticeable change in head orientation away from the operating field. Focus shifts were determined as an absolute value per participant per task. Focus shifts demanded by the task (eg, looking for the next tool) were not included.

Workspace Efficiency

This analysis determined the number of times and for how long the mentee's arms would have collided with the tablet, had one been present. Before the participants' arrival, the 3D position in the workspace of a tablet that was placed over the patient simulator was acquired with a depth camera. This position was treated as constant throughout the entire experiment. The skeletal tracking data of each participant was used to assess whether the participants' forearm intersected the hypothetical tablet's position. The total number of collisions and their duration (both as an absolute value and as a ratio of the total completion time) were calculated.

Responses to the Questionnaire

Participants filled a usability questionnaire regarding the used telementoring system. Participants answered the questions on a 5-level Likert scale from ''Strongly Disagree'' to ''Strongly Agree'' (1–5, respectively). Overall scores were calculated among all the participants.

Statistical Analysis

The statistical analysis was based on the comparison between two populations: participants using STAR and participants using telestrator. The normality assumption of the data was evaluated using the Shapiro-Wilk test.[30] When data pointed to non-normality, the nonparametric Wilcoxon rank-sum test[31] was used to compare the two populations. In contrast, a *t* test using the Satterthwaite condition for nonequal variance[32] was used when the normality assumption was supported. The data were summarized as mean (μ) $\pm$ standard deviation (σ_x) for normally distributed data, and as median $\pm$ interquartile range (IQR) for non-normal distributed data.

For the placement error metric, the best and worst results were extracted from each condition, giving n = 24 for the first task and n = 8 for the second. For completion time and focus shifts, the comparisons were made with n = 30 for the first task, and n = 10 for the second.

RESULTS

The following subsections present the study results.

Placement Error

For Task 1, participants in the STAR condition (μ, 11.37 mm; σ_x, 0.72 mm) presented 45% less ($P < 0.001$) average placement error than those in the conventional telestrator condition (μ, 20.73 mm; σ_x, 5.11 mm). For Task 2, participants using STAR (μ, 8.606 mm; σ_x, 0.806 mm) presented 14% less ($P = 0.01$) average placement error than those using telestrator (μ, 9.95; σ_x, 1.07 mm).

Task Completion Time

Participants in the STAR condition (median, 46.210; IQR, 21.8 s) completed Task 1 31% slower ($P < 0.001$) than those in the telestrator condition (median, 31.85; IQR, 12.8 seconds). Participants using the STAR platform (μ, 256.8; σ_x, 56.2 seconds) performed Task 2 24% slower ($P = 0.013$) than those using telestrator (μ, 194.1; σ_x, 31.6 seconds).

Focus Shifts

For Task 1, participants in the STAR condition (μ, 0.83; σ_x, 0.97) performed 92% less ($P < 0.001$) focus shifts in average than those using telestrator (μ, 11.10; σ_x, 3.33). For Task 2, participants using STAR (median, 4.00; IQR, 7.00) performed 88% less ($P = 0.0039$) focus shifts in average than those using telestrator (median, 34.50; IQR, 14.75).

Workspace Efficiency

Table 1 summarizes the results of the workspace efficiency analysis. The ARHMD avoided 4.8 collisions for Task 1 on average, and 3.8 collisions for Task 2. The duration of the potential collisions on average was 3.2 and 1.3 seconds, respectively. For some participants, Task 1 implied as many as 27 collisions, totaling 51% of the task completion time.

Questionnaire Responses

Participants considered the STAR platform to be more favorable in terms of telementoring capabilities offered (4.71 vs 4.50); ease of use (4.43 vs 4.38); ease to follow instructions (4.71 vs 4.38); information exchange efficiency (4.43 vs 3.88); and reduction of time taken (4.29 vs 4.00). Likewise, participants commented that STAR had a less negative impact in frustration (4.57 vs 3.88) and in time taken to complete the procedure (4.14 vs 3.88). Participants commented that the STAR platform is useful and interesting, but it had a limited FOV and its imagery may produce head discomfort and ocular fatigue when the device is not adjusted correctly.

DISCUSSION

When compared against conventional telestrators, placement error and focus shifts were significantly reduced with the ARHMD. Participants did not have to shift focus to receive instructions, leading to reduced cognitive load and error accumulation.[5] In addition, the platform's 3D visualization preserved depth perception to afford a more natural mapping between the annotation's source and destination.

However, completion time was higher when using the ARHMD. Because participants were observing the absolute 3D position in which the annotation was supposed to be located, they tried to match the location as closely as possible, which led to increased task completion times. This is consistent with our previous work[5] and with speed-accuracy tradeoff literature:[33–35] providing more opportunities to refine placement is linked to increased task completion times.

The questionnaire revealed more positive attitudes toward the ARHMD condition than to the telestrator condition. Most ARHMD users expressed that the system created a more immerse experience, both with their comments and scores in the questionnaire. Some questionnaire responses do not match the results of the statistical analysis performed, specifically those regarding the time taken to complete the tasks. Nevertheless, the questionnaire suggests that participants preferred using STAR and perceived an improvement in their performance.

Switching from a 2D to a 3D environment enhanced the STAR platform beyond its previous tablet-based interface. The ARHMD acted as a fully transparent display, favoring immersion and creating a more natural experience as it preserved binocular depth cues, crucial when performing dexterous tasks. The workspace efficiency analysis reveals that collisions would have occurred had a tablet been present. Therefore, the presence of a tablet would have interfered with mentees' free selection of body poses and motions during their performance; participants would have to assume less comfortable poses to avoid collisions when a tablet is in use. In addition, the ARHMD is easier to deploy, and lets the user move freely and observe annotations from different angles. However, this HMD system should not be seen as a replacement of the previous STAR tablet-based platform, but rather as a portable, first-response version of the system. For example, even if the ARHMD system excels in austere scenarios that require in-situ attention to stabilize the patient, the live video feedback it provides would not be in a static position, which is a given when using the STAR tablet device.

TABLE 1. Summary of Workspace Efficiency Analysis. Collision Durations of Over 50% of the Total Time Taken Demonstrate the Encumbrance of Tablet-based Systems

		Task 1			Task 2
Metric		Trial 1	Trial 2	Trial 3	
Number of collisions	AVG	5.7	4.6	4.1	3.8
	MAX	24	27	14	24
Collision duration	AVG	4.4s	2.5s	2.7s	1.3s
		8.7%	7.6%	7.8%	0.68%
	MAX	28.8s	13s	17s	15.7s
		43%	51%	39%	8.8%

Current limitations include ARHMD hardware constraints such as intermittent 3D imagery drift and reduced FOV through which the annotations can be seen. In addition, the graphical annotations shown to the ARHMD user are based on an approximated model of the human visual system; a more robust calibration process is required to ensure proper depth perception for each user. Future work will explore an individually-tailored system calibration, and broadcast of the mentee's first-person perspective to the mentor. Moreover, although medical students and a simple task setup are the reasonable placeholders for a medic requiring telementored guidance, as our system matures its usefulness needs to be validated in more complex scenarios and with populations consisting of surgery residents and general surgeons.

CONCLUSION

This work evaluated the telementoring capabilities of the STAR platform based on an Augmented Reality Head-Mounted Display (ARHMD). The system was compared against a conventional telestrator device (guidance in a nearby monitor). Participants completed tasks regarding anatomical landmarking and a mock abdominal incision procedure. Although participants using the STAR platform completed the task slightly slower than those using telestrator, the placement error and number of focus shifts were significantly reduced. A post-experiment questionnaire revealed that participants using STAR had a more immersive experience and an improved information exchange with the mentor. Moreover, an analysis of the participants' arms movements revealed that the ARHMD allowed them to perform more natural movements and use their workspace more efficiently, an improvement when compared to our previously reported tablet-based system. This study suggests that ARHMD devices can improve surgical performance during telementoring by displaying augmented 3D annotations directly into the users' FOV.

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