Collocated AAR: Augmenting After Action Review with Mixed Reality

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ABSTRACT

This paper proposes collocated After Action Review (AAR) of training experiences. Through Mixed Reality (MR), collocated AAR allows users to review past training experiences in situ with the user's current, real-world experience. MR enables a user-controlled egocentric viewpoint, a visual overlay of virtual information, and playback of recorded training experiences collocated with the user's current experience. Collocated AAR presents novel challenges for MR, such as collocating time, interactions, and visualizations of previous and current experiences.

We created a collocated AAR system for anesthesia education, the Augmented Anesthesia Machine Visualization and Interactive Debriefing system (AAMVID). The system was evaluated in two studies by students (n=19) and educators (n=3). The results demonstrate how collocated AAR systems such as AAMVID can: (1) effectively direct student attention and interaction during AAR and (2) provide novel visualizations of aggregate student performance and insight into student understanding for educators.

KEYWORDS: Mixed Reality, After Action Review, Anesthesia Machine, User Studies

INDEX TERMS: J.3 [Computer Applications]: Life and Medical Sciences – Health;

1 INTRODUCTION

This paper presents and evaluates collocated after action review (AAR) implemented via Mixed Reality (MR)[7]. In training applications (e.g. military [15] and medical training [10]), MR collocates real and virtual information, which can enhance visualization, interaction, and learning during training. However, MR is rarely used after the experience (the AAR phase). Most current AAR systems consist of reviewing videos of a student's training experience, which allows students and educators to playback, critique, and assess performance. However, video-based review consists of fixed viewpoints and primarily real-world information (i.e. no virtual overlay or augmentations as found in MR). We propose to augment after action review with MR to facilitate collocated AAR. The overlay of virtual information and user-controlled egocentric viewpoint obtained with MR may enhance after action review and provide novel interaction and visualization that is not possible with current AAR systems.

Specifically, this paper presents a MR-based collocated AAR system – the Augmented Anesthesia Machine Visualization and Interactive Debriefing system (AAMVID). It merges the playback features of AAR with the augmentation features of MR. AAMVID features include a user-controlled review experience from a first-person viewpoint. Users can review an abstract simulation of an anesthesia machine's internal workings that is registered to a real anesthesia machine (figure 1). During the AAR, previous interactions are collocated with current real-time interactions (figure 1 bottom) – enabling interactive instruction and correction of previous mistakes in situ (i.e. in place with the anesthesia machine). Similar to a video-based review, AAMVID meets many of the educational needs of educators and students by offering recording and playback controls. Further, AAMVID collocates these recorded experiences with the anesthesia machine and the user's current real-world experience.

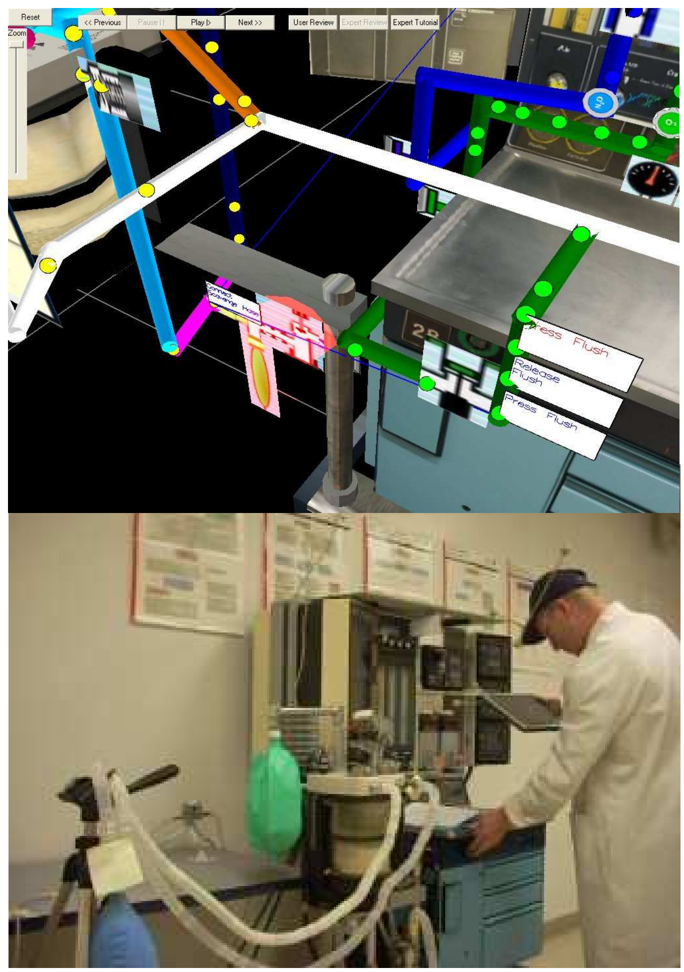

Figure 1. *Top*: a student view from a magic lens *Bottom*: a student mimics the collocated expert interaction.

To be useful, collocated AAR must meet the pedagogical needs of educators and students. Students need directed instruction, repetition (deliberate practice), and feedback to bring them to a level of competency. Educators need to assess students'

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approaches to problems. To make this assessment, they need to identify means, outliers, and class-wide trends.

Because of the different educational needs of educators and students, two versions of AAMVID were created and evaluated separately. The student version (AAMVID-S) enables students to review and interact with both their own previous interactions and an expert's previous interactions. The educator version (AAMVID-E) enables educators to visualize and interact with the aggregated performance of multiple students. Both the student and educator visualize this data in situ with a real anesthesia machine.

Collocated AAR merges previous experiences from multiple users (e.g. students or experts) with the real-time experience. This collocation of experiences offers a novel type of interactive AAR. To enable this type of experience, the following MR research challenges must be addressed in a collocated AAR system:

- Time – collocating playback time with real time
- Interaction – collocating recorded expert or student interactions with current interactions
- Visualization – collocating recorded users' viewpoints and virtual information with the current user-controlled view.

In this paper, we propose an MR-based approach that addresses these needs. The approach is evaluated in two usability studies. In the first study, 19 students learned about anesthesia machines and then used AAMVID-S to review their experiences. Then three educators used AAMVID-E to review the aggregate data obtained from the 19 study participants. These studies aimed to determine whether MR-based collocated AAR is a viable and effective pedagogical tool.

This paper is organized as follows. In sections 2 and 3, we describe relevant previous work. Then, section 4 describes the concept of collocated AAR and the challenged to MR. In sections 5 and 6 we describe the design and usability evaluation of AAMVID-S for students. Finally, in sections 7 and 8 we describe the design and usability evaluation of AAMVID-E for educators.

2 Previous Work

2.1 Magic Lens Displays

In AAMVID, the main visual display is a tracked 6DOF. Magic Lenses were originally created as 2D interfaces, outlined in [1]. 2D magic lenses are movable, semi-transparent 'regions of interest' that show the user a different representation of the information underneath the lens. They were used for such operations as magnification, blur, and previewing various image effects. Each lens represented a specific effect. If the user wanted to combine effects, two lenses could be dragged over the same area, producing a combined effect in the overlapping areas of the lens. The overall purpose of the magic lens was to show underlying data in a different context or representation. This purpose remained when it was extended from 2D into 3D [9]. Instead of using squares and circles to affect the underlying data on a 2D plane, boxes and spheres were used to give an alternate visualization of volumetric data.

In Mixed and Augmented Reality these lenses have again been extended as in [6]. The MR/AR lens is similar to the original 2D magic lens metaphor, but has been implemented as a 6DOF tangible user interface [4,10] instead of a 2D GUI.

2.2 Integrative Modeling

Integrative modeling – the concept of linking dynamic and geometric models together in the user interface – is introduced in [3, 8]. Our work with the AAMVID utilizes this concept, using MR to realize the linkage with an effective form of human-machine interaction. In particular, MR and tangible user interfaces [4] provide an engineering approach to collocating: components of an abstract anesthesia machine simulation model, components of a real anesthesia machine, and visualizations of previous training experiences (e.g. interactions performed).

2.3 After Action Review

2.3.1 History

After Action Reviews (AAR) originally stem from the "war games" practiced in military command strategy review (e.g. outcomes after moving troops). AAR was later developed to review combat missions and training exercises for both commanders and soldiers. For example AAR allowed soldiers, "to discover for themselves what happened, why it happened, and how to sustain strengths and improve on weaknesses" [13]. Since then, AAR has been extended into the industrial, medical, and educational domains.

2.3.2 After Action Review Systems

There are numerous AAR systems for many fields of training. For military training, TAARUS [14] and DIVAARS [15] use maps and graphs to allow AAR of troop movements and of battlefield simulations. More generally, behavior has been studied using AAR. For example, Phloem [16] visualizes large sets of behavioral data.

AAR has been used for review of virtual experiences as well. IPSVis [11] is an AAR system geared towards Interpersonal Simulation, specifically Human-Virtual Human interaction. Medical students use IPSVis for AAR of physician-patient interviews using virtual human patients. IPSVis was shown to impact students' self-perception.

Collocated AAR builds upon these previous approaches to AAR. Unlike the previous AAR systems, collocated AAR takes place in situ with the training area. Thus, users perform collocated AAR in the same space that they trained, rather than at a desktop. Furthermore, this collocation could potentially reinforce training by enabling users to review expert interaction in situ – thereby increasing the overall educational benefits of the AAR.

Outside of AAR, there has also been some relevant work in using expert interactions to direct training. Chua et al. [18] created a system to train students with expert Tai chi movements from a user controlled, first person perspective. Sielhorst et al. [19] created new ways of quantitatively comparing expert and novice 3D interactions in Augmented Reality (AR) with an application to forceps delivery training. In addition, Sielhorst et al. effectively collocated the novice and expert interaction visualizations.

2.3.3 Video-Based AAR in Education

In training and education (e.g., healthcare and anesthesia education), students need repetition, feedback, and directed instruction to achieve an acceptable level of competency, and educators need assessment tools to identify trends in class performance. To meet these needs, current video-based AAR systems offer educators and students the ability to playback (i.e. play, fast forward, rewind, pause) training sessions repeatedly and at their own pace. Some video-based AAR systems (such as Studiocode [17], which costs $25,000) allow educators to manually annotate the video timeline – to highlight important moments in the video (e.g. when a mistake was made and what kind of mistake). This type of annotation helps to direct student instruction and educator assessment.

Video-based AAR is widely used in training because it meets many of the educators' and students' educational needs. However, video-based review consists of fixed viewpoints and primarily real-world information (i.e. the video is minimally augmented with virtual information). Thus, during AAR, students and educators do not experience the cognitive, interactive, and visual advantages of collocating real and virtual information in MR.

3 THE AUGMENTED ANESTHESIA MACHINE

AAMVID is an extension of our previous work with the Augmented Anesthesia Machine (AAM) [10]. The AAM is an MR-based system that was created to enhance learning and training in anesthesia education. AAMVID is built as an AAR module upon the core AAM system. This section describes the training benefits of the AAM, and aims to motivate the use of AAMVID to enable similar benefits in collocated AAR.

3.1 Enabling Transfer from Abstract to Concrete with MR

Currently, some anesthesia students first train with the Virtual Anesthesia Machine (VAM) (figure 2), a 2D abstract, transparent reality simulation [5] of an anesthesia machine. One of the advantages (and disadvantages) of the VAM is that its spatial organization is simpler than a physical machine. This simplification makes abstract concepts (such as gas flow) easier to visualize, follow, understand and retain [2].

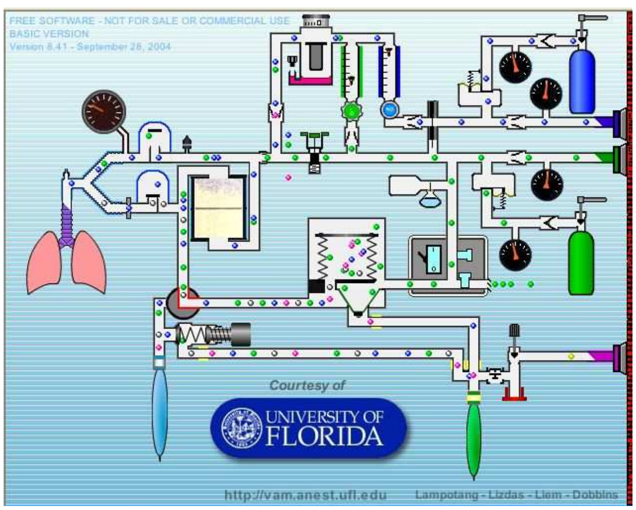

Figure 2. A screenshot from the VAM.

After students practice with the VAM, they move on to practice with a real anesthesia machine. The anesthesia machine allows students to learn the procedural concepts (e.g. how to physically interact with the machine). However, some students have difficulty transferring and applying the VAM's abstract concepts when interacting with the physical machine. It was hypothesized that students encounter this problem because they have difficulty spatially mapping the simplified VAM layout to the more complex physical machine layout.

In previous research, the AAM was presented as a potential solution to this problem. The AAM is offers students the ability to (1) use a tracked 6DOF magic lens (figure 1 bottom) to visualize an abstract 3D simulation of the anesthesia machine's internal components and invisible gas flow (figure 3), while (2) interacting with the real anesthesia machine. The AAM helped users to better transfer their abstract knowledge of the machine (i.e. invisible gas flows) to a concrete domain (i.e. physical interaction with the machine) [10]. Later it was shown that this improvement was in part the result of the AAM compensating for low spatial cognition [12]. Based on these findings, we expect that the AAM's benefits will transfer from collocated training to collocated AAR.

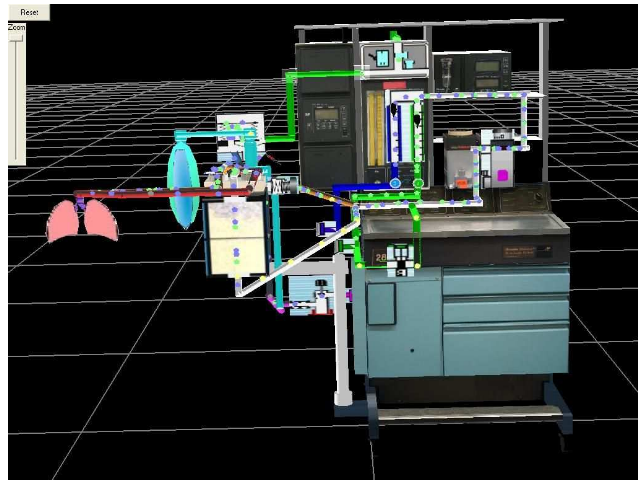

Figure 3. A zoomed-out screenshot of the AAM simulation.

4 COLLOCATED AAR: CHALLENGES FOR MR

The main challenge of MR-based collocated AAR is to merge the abilities of MR with the goals of AAR.

Video-based AAR system goals**:**

- Enable users to visualize and compare user interactions to that of experts
- User-controlled playback of the video for ease of review (e.g. fast forward, pause, rewind).

MR abilities:

- Visual overlay of virtual information (e.g. the abstract simulation in the AAM)
- Interaction with the real world (e.g. turning knobs on the anesthesia machine) that affects the visual overlay.
- User-controlled viewpoint.

For collocated AAR, a MR system must collocate things that are not typically collocated, such as playback time with real-time, recorded interactions with current real-world interactions, and recorded virtual information with current virtual information.

4.1 Collocating Time

To enable playback in collocated AAR, a system must be able to record entire experiences and play back the experiences in situ with the user's current real world experience. Thus at any given point in the review process, there are at least two collocated timelines: (1) the recorded experience timeline and (2) the real-time timeline. The user can control the recorded timeline but obviously real time cannot be controlled. Thus, these two timelines are not synchronized or consistent. This could potentially cause visual confusion and must be addressed in a collocated AAR system.

Moreover, users may have control over playback of more than one timeline, such as the user's previous timeline and an expert's previous timeline. Interacting with time is a difficult interface problem because time controls (e.g. pause, play) add an extra degree of freedom. If we allow the user to control n collocated timelines, then we add n degrees of freedom to the interface. To address the challenge of collocating time, a system must address how to record timelines, how many timelines can be collocated in one space, and how users can control the playback of each timeline.

4.2 Collocating Interaction

In a collocated AAR system, users should be able to review past interactions and visualize feedback from current, real-world interactions (e.g. interacting with an anesthesia machine). The main issue with collocating recorded and present interactions is concurrency. A user may physically turn knob A to the left while the played back interaction indicates that knob A is turned to the right. If turning the knob updates the augmented visualization or simulation, this will cause a conflict in visual feedback. Thus a collocated system must decide if the virtual representation of the knob is turned left, right, or some combination of the two concurrent interactions.

4.3 Collocating Visualization

MR systems facilitate the visual overlay of virtual information (e.g. the AAM's abstract simulation). However, in collocated AAR, it is challenging to represent past and present virtual information in the same visually collocated space. Each previous experience that is reviewed in AAR (e.g. a user's experience, an expert's experience) has specific visualizations that are associated with it, such as the positions and orientations of virtual objects (e.g. invisible gas particles in the AAM). A collocated AAR system could visually collocate all the virtual objects from all the playback timelines into one space or visually collocate a subset of these objects. These challenges must be addressed in a collocated AAR system.

5 AAMVID-S For Students

AAMVID-S is a MR-based system for collocated AAR of anesthesia machine fault tests in anesthesia education. First a fault is caused in the machine – a problem in the machine unknown to the student and intentionally caused by the educator, such as a disabled component. Then students attempt to diagnose and correct the machine fault by interacting with the real anesthesia machine (with no help from additional visualizations or simulations). Once this test is completed, students can use AAMVID-S for the collocated AAR of the test. This section describes the AAMVID-S implementation and presents the results of a usability study with 19 students.

5.1 AAMVID-S System Features

The goals of AAMVID-S are to allow students to (1) review their performance in situ, (2) review an expert's performance for the same fault in situ, (3) interact with the physical anesthesia machine while following a collocated expert guided tutorial, and (4) observe a collocated visualization of the machine's internal workings during (1),(2),and (3). To realize these goals in MR, we used a tracked 6DOF magic lens display and designed software that logged student and expert interactions. During the AAR, AAMVID-S allows a student to playback previous interactions, visualize the chain of events that made up the previous interactions, and visualize where the user and the expert were each looking during their respective interactions.

One important design decision is that AAMVID only allows students to control the playback of one previous experience at a time (e.g. a user's previous experience or the expert's experience). The purpose of this decision is to decrease student confusion. However, AAMVID does visualize interactions from a recorded experience in situ with the user's current real world experience and interactions.

5.1.1 Logging Student and Expert Interaction

To generate visualizations for collocated AAR, two types of data are logged during the fault test: head-gaze and anesthesia machine states. For head-gaze the user wears a hat (figure 1 bottom), tracked with retro-reflective tape and IR sensing web cams. This enables the system to log the head-gaze direction of the user. For the anesthesia machine state, the AAM tracking system, described in [10], tracks the states of the machine. The changes in these states are then processed to determine when the user interacted with the machine.

A student log is recorded when a student performs a fault test prior to the collocated AAR. Our expert log data was recorded when Dr. Samsun Lampotang – an anesthesia educator and a co-author of this paper – performed each of the fault tests.

5.1.2 Abstract Visualization of Machine Faults

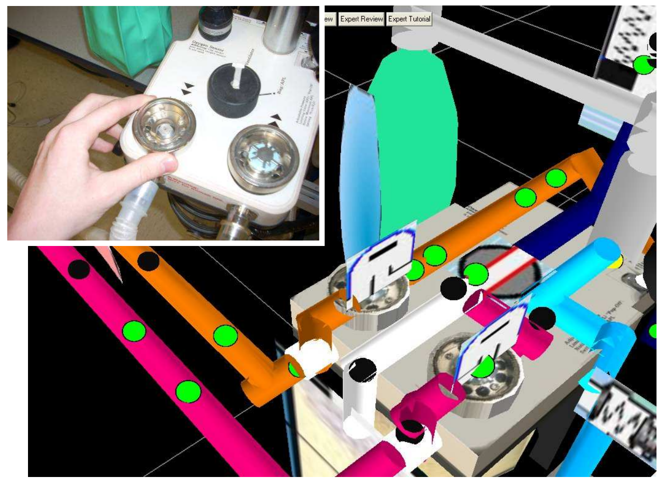

Figure 4. *Top left*: real-world view of a user touching an incompetent inspiratory valve. *Bottom:* AAMVID view of an incompetent inspiratory valve during AAR.

In AAMVID-S, students physically interact with the real machine and use a 6DOF magic lens to visualize how these interactions affect the internal workings and invisible gas flows of the real machine. Similarly, to visualize fault behavior, specific faults were physically caused in the real machine and triggered in the abstract simulation. For example, one fault involves a faulty inspiratory valve, which can be potentially harmful to a patient. Figure 4 top left is what the student sees in a real machine. Figure 4 bottom is what the student sees on the magic lens during the AAR. Because the magic lens visualizes abstract concepts like invisible gas flow, AAMVID-S allows students to observe how a faulty inspiratory valve affects gas flow in situ. Notice how the abstract valve icons are both open (e.g. the horizontal line is located at the top of the icon, which denotes an open valve).

5.1.3 Event Chain Visualization

To learn from and critique their fault tests, students need to review the specific actions they performed during the fault test and compare their actions to an expert's actions. To meet this need, AAMVID-S enables students to visualize the chain of interaction events that occurred during the fault test. For example, a student or expert might have turned the O_2 flow control knob, then turned on the ventilator, and then pressed the oxygen flush. AAMVID-S discretizes this series of events on the fly during the fault test.

To discretize these events, the AAMVID-S uses a logging system coupled with the internal simulation of the machine. The AAMVID-S logging system is built upon the AAM system, which simulates the gas flow and internal states of the components with a rule-based finite state machine [20] (FSM). This FSM takes input from the AAM tracking system. Based upon this input, the AAM updates the visualized internal machine states and gas flows. Changes in the internal states then are used to detect specific interactions events (e.g. when the user turns the O2 knob, the FSM changes state and the simulated O2 particles visually increase in speed). When an interaction is detected, the state of the simulation is key framed (i.e. saved in memory) for later playback.

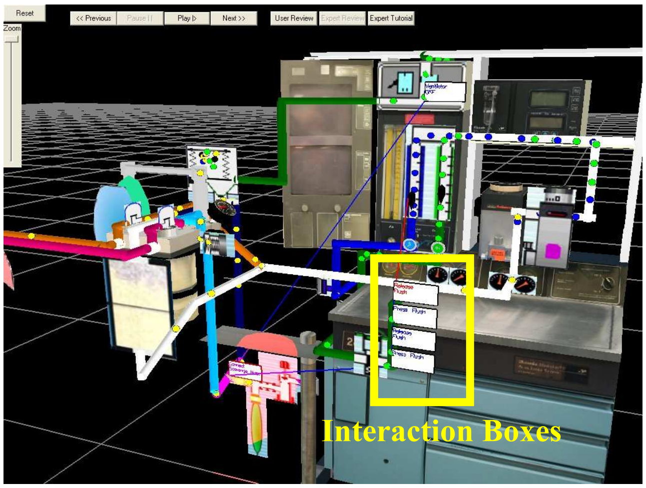

Figure 5. Past interaction boxes are collocated with the real controls and describe past interactions. The boxes are connected with lines, denoting a chain of interaction events.

When an event occurs during playback, an "interaction event box" appears that is collocated with the corresponding control (figure 5). For example, when the student turned the O_2 knob, an interaction box pops up next to the control and reads that the student increased the O_2 flow by a specific percentage. To direct the user's attention to the next event, a 3D red line is rendered that slowly extends from the last interaction event position and towards the position of the next upcoming event. Lines between older events are blue lines indicating that the events have passed. By the end of the playback timeline, these lines connect all the interactions that were performed in the experience. This forms a directed graph where the interaction boxes are the nodes and the lines are the transitions between them.

5.1.4 Playback: Manipulating Virtual Time

An advantage of traditional video-based AAR systems is the ability to play, pause, rewind and fast-forward. AAMVID-S implements this playback interface with 2D buttons that users click with a pen interface. AAMVID-S users are able to jump (fast forward) to the next interaction event, jump (rewind) to the previous event if they missed something, or pause the playback to observe the interaction at their own pace. One additional advantage of AAMVID-S is that it allows students to view any point in time from a user-controlled viewpoint. For example, students can pause the interaction playback and then move to a different viewpoint to visualize a key point in time or previously occluded information (i.e. internal gas flows).

5.1.5 Look-at indicator

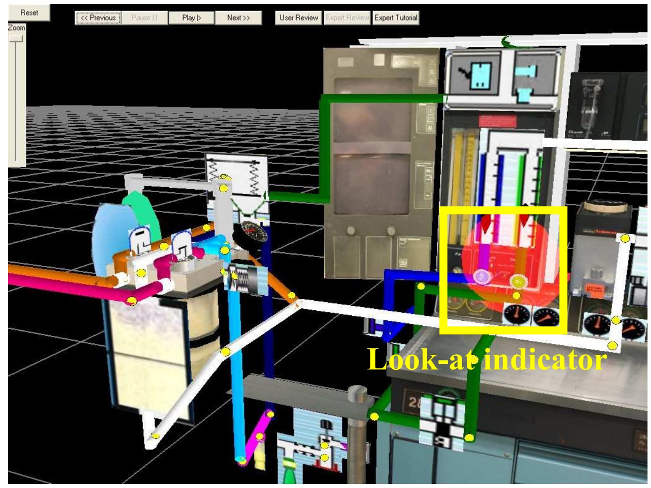

Figure 6. The student can see what an expert was looking at, denoted by the large red spotlight.

One of the difficulties that students experience in a fault test (and in the AAR of a fault test) is in knowing where to direct their attention. There are many concurrent processes in an anesthesia machine and it can be difficult for students to know where to look to find the faults. To resolve this problem in the collocated AAR, students can see a visualization of where they were looking or where the expert was looking during the fault test (although not at the same time). To generate this visualization, we tracked the head of each student and of our expert. The resulting "look-at indicator" (the highlighted spotlight in figure 6) helps students to direct their attention in the AAR and allows them to compare their own observations to the expert's observations.

5.2 Viewing Modes

One important design decision was that AAMVID-S only allows students to control the playback of one previous experience at a time. We expected that control and visualization of multiple played back experiences would complicate the visual feedback and confuse students. Instead, AAMVID-S splits its sources of data into three modes. Thus, using the aforementioned visualization and interaction techniques, there are 3 different viewing modes that visualize data from different sources. Each of these modes corresponds to specific sets of data that are being collocated with the real world. These modes are described below.

5.2.1 User View Mode

This mode visualizes the student's fault test collocated with the real machine. During this mode, the real machine is off (electrical and pneumatic power shut off) to minimize conflicting processes that are visualized in the abstract simulation. For example, it might be confusing to students if the ventilator was on (bellows cycling up and down) during their interaction visualization, but off in the real world. We expected that if students knew that the machine was off, they would treat it as a place holder during the review experience – serving only to put the review experience in context with the machine.

5.2.2 Expert View Mode

This mode visualizes the expert's fault test collocated with the machine in the same way that User View Mode visualizes the user's fault test (the machine is also off during this mode for the same reasons as during User View Mode). This type of interactive visualization makes the expertise of the domain expert (whose time is usually in short supply) readily available to essentially an unlimited number of learners and novices at any time. In essence, the collocated AAR with expert interaction makes expertise available on demand.

5.2.3 Expert Tutorial Mode

This mode directs student attention to an interaction with the overlaid interaction event boxes and look-at indicator of the expert, but the student must perform the interactions because the abstract simulation visualization comes from the real time tracking data of the anesthesia machine, which is turned on during this mode. This enables the student to (1) visually follow the expert's interactions, (2) physically mimic the interactions (figure 1) and (3) visualize how these interactions affect the internal workings of the machine in real-time. This promotes a more hands-on learning experience.

6 AAMVID-S Usability Study

A study was conducted to determine the usability of AAMVID-S and more generally to identify the advantages and disadvantages of collocated AAR. We wanted to determine if collocated AAR is viable. In the study, 19 students enrolled in an Introductory Psychology course were first trained using the AAM. Then they were given three machine fault tests. After each test, they used AAMVID-S for AAR, which was performed without an expert present and with minimal assistance from the experimenter (i.e. the experimenter would answer interface-related questions but not anesthesia-related questions). Each participant was given a questionnaire before and after the AAR to gauge how collocated AAR affected (1) understanding of the machine faults and (2) their level of confidence in their answers.

The main purpose of this study was to evaluate our design decisions for AAMVID-S. Because AAR in gneral increases confidence and understanding in students, we expected to observe the same benefits with collocated AAR, but our main aim was to obtain feedback from students about our collocated AAR system design approach. In the future we plan to formally compare AAMVID-S to a video based system in order to assess the specific benefits of collocated AAR.

6.1 Study Procedure

For each participant, the study was conducted over a period of two days (figure 4). The first day consisted mostly of anesthesia machine training. The second day included hands-on tests with the real machine. Participants performed an AAR for each of the hands-on tests. The second day also included several questionnaires about their opinions of the training and AAR modules and personal information (e.g. computer usage and experience, Grade Point Average – GPA).

Day 1 (~90 minute session):

1. Introduction: Participants were provided a manual, which first gave them an introduction to the VAM. The manual was used in conjunction with an online interactive tutorial, which highlighted and explained each of the major VAM components and subsystems. The VAM simulation was used to direct the intro because the VAM is an intrinsic component of the AAM as its computational media.
2. Complete 5 exercises: Each participant completed the same 5 exercises by following the manual and interacting with the AAM. Each of the exercises focused on a specific anesthesia machine concept (i.e. a particular component or subsystem).

Day 2 (~90 minute session):

For logistical reasons and to prevent participant fatigue and avoid testing superficial knowledge and short-term retention, we attempted to have a time interval of 24 hours between the Day 1 and Day 2 sessions.

1. Tracked 6DOF Hat Calibration – To track participants' heads during the subsequent tests, participants wore a tracked 6DOF hat. The hat was tracked with the same optical IR-based system as the magic lens. For calibration, the student first wore the hat and faced the machine. The base orientation of the hat was recorded. Each student was then asked to look at four different components on the anesthesia machine and the pitch of the tracked orientation was adjusted manually to match these components. This step was taken to improve the accuracy of head-gaze data and potentially better correlate head-gaze to actual eye-gaze.
2. Three Hands-on Anesthesia Machine Fault Tests/AAR: For each participant, the tests were given in random order. For each test, the investigator first caused a problem with the machine (e.g. disabled a component). Participants were then told that there may or may not be a fault present. Participants then had to find and diagnose the problem. After each test, participants performed a collocated AAR session with AAMVID-S using each of the three viewing modes.
3. Personal / Opinion Questionnaires: Participants were asked several personal questions (e.g. computer experience) and what, in their opinion, were the most effective and least effective parts of the training and AAR modules.

6.2 Metrics

Understanding – Right after each fault test, participants wrote down what they thought the fault was, and how to correct it. Then they went through collocated AAR with AAMVID-S on their own. After the AAR, they again assessed what the fault was, and how to correct it. To measure change in understanding, we measured the change in the quality of their answers. Each fault test was scored on a scale of 0 to 4, 4 being the best possible answer.

Confidence – Right after each fault test, participants wrote down how confident they were that their solution to the fault was correct. Then they went through collocated AAR with AAMVID-S. After the AAR, they again reported their confidence in their answers. Participants rated the confidence in their answers on a scale of 0 to 4, 4 being very confident.

Subjective Benefits to the User – In a questionnaire, we queried what parts of AAMVID-S (e.g. User View Mode, Expert Tutorial Mode, look-at indicator) were most helpful. We also asked questions about usability and potential reuse for future AAR experiences. Opinions were given on a 5-point Likert scale.

6.3 Results

This section presents and discusses the results of the study. It is organized by the metrics used: understanding, confidence, and subjective benefits.

6.3.1 Discussion of Understanding

As expected of an AAR system, AAMVID improved participant understanding of machine faults (figure 7). Prior to the AAR, most participants misdiagnosed the fault or thought that there was no fault after completing each fault test. However, once participants used AAMVID to review the fault, they were able to correct the fault in the real machine and changed their original answers to the correct answers. This suggests that their understanding increased significantly.

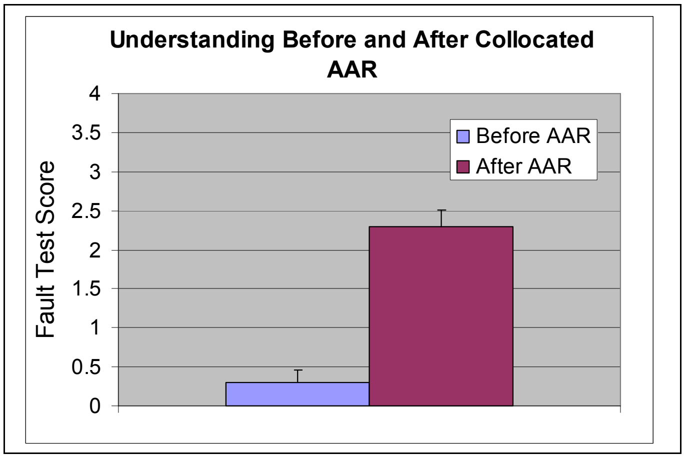

Figure 7. Understanding before and after collocated AAR shows a significant increase ($p < .001$). Standard error bars are shown.

However, scores were not perfect (4.0) even after students reviewed an expert's experience. We expect that understanding and confidence may not have reached full potential in part due to the "interaction box" visualization approach. For example, during a fault test where an N_2O valve was closed, the expert interaction box told the participants to "Open the N_2O valve". Some participants thought the problem was that the N_2O valve was open, which led them to think that the answer was to close the valve. However, the valve was already closed and the participant had to open the valve to solve the fault correctly. This demonstrates a disadvantage of using an abstract "interaction box" approach to visualizing interactions. These observations suggest that overlaid written directions (as found in many MR systems) are not always enough to elicit correct interaction. In this case, a video based review might have been more helpful.

6.3.2 Discussion of Confidence

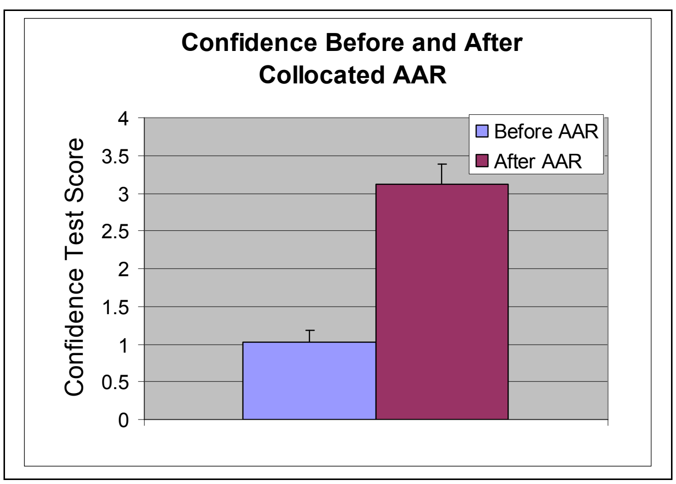

Figure 8. Confidence before and after collocated AAR shows a significant increase ($p < .001$). Standard error bars are shown

As expected of an AAR system, AAMVID increased participant confidence in their answers to questions of how to correct the faults and what effect the faults had on the patient (figure 8). Prior to the AAR, participants had relatively low confidence in their assessment of the faults. However, after participants used AAMVID for AAR, their confidence significantly increased. This increase in confidence and understanding supports the notion that AAMVID is a viable AAR system.

6.3.3 Discussion of Subjective Benefits

Most participants expressed that they would use the magic lens for machine fault study in the future because the magic lens was a useful tool in helping them to understand machine faults. Specifically, participants expressed that the "Expert tutorial Mode" was the most helpful AAMVID mode. Expert tutorial mode overlaid an expert's interaction boxes and "look-at indicator" in situ with the real anesthesia machine and the abstract simulation. This mode allowed participants to observe and physically mimic the expert's collocated interactions. Participants found the expert tutorial's interaction boxes and look-at indicator easy to follow and noted how they preferred the mode's more "hands-on experience". This suggests that AAMVID's collocated interaction boxes and look-at indicator approaches are an effective way to focus a student's attention and direct them where in the training space to interact.

Some participants noted that they did not like the DVD player interface (e.g. 2D buttons: play, pause) for the playback controls. They found this interface cumbersome and unintuitive to use with the magic lens display's pen. This suggests that there are ergonomics issues with integrating a hand held 6DOF magic lens with 2D time manipulation. Participants typically held the tablet in the non-dominant hand and used the pen with the dominant hand. The weight of the tablet in the non-dominant hand coupled with the position of the buttons on the screen could have become cumbersome over time. A problem could also be that unlike manipulation of virtual objects in space, there are very few interface metaphors for the manipulation of virtual time. Users might benefit from a different type of interface (e.g. a 3D interface).

7 AAMVID-E FOR EDUCATORS

With AAMVID, educators do have the ability to review individual student interactions, but they are often more interested in visualizing aggregate data to assess class-wide performance. Educators may be interested in identifying trends (e.g. many students may approach the same problem incorrectly) and outliers (e.g. the few students who perform exceptionally well or poorly). To meet this need, AAMVID-E can combine data from multiple students and visualize this data via the magic lens. Currently, AAMVID-E displays aggregate head-gaze and interactions (i.e. turning knobs, pressing buttons).

7.1 Gaze Maps

A visualization of gaze can help educators better understand the main components that students focus on during a fault test, and allows them to adjust their education plans (e.g., lectures) accordingly. To enable gaze visualization, AAMVID-E generates a heat-mapped (i.e. the places where participants focused on appear more "hot" in color) visualization of where students were looking during a fault test (figure 9).

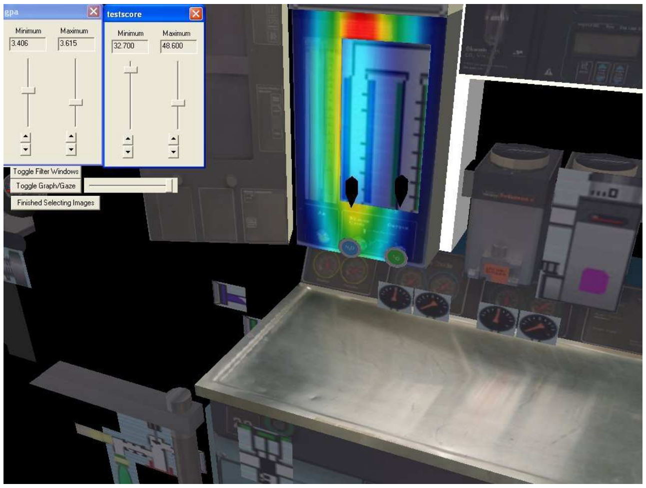

Figure 9. A gaze map collocated with the machine. In this case, many students were looking at the flow meters during the fault test. This data can be interactively filtered using the slider controls in the top left.

7.1.1 Implementation of Gaze Maps

Our method of generating gaze maps is described in this section. Note, however, that there may be more efficient methods to generate the gaze maps. Our gaze mapping method utilizes an image-based approach, which requires a significant amount of preprocessing time to facilitate the rendering of gaze maps at interactive rates. This method requires a 3D model of the geometry that the gaze maps will overlay. In the case of AAMVID, we used a scale 3D model of the real machine (shown in figure 9). This model must be registered to the real object (e.g. the anesthesia machine) that users were gazing at during the experience.

Preprocessing for every data point in a student's log:

1. Get Head position and orientation
2. Project 4 rays of the viewing frustum (generated by the head tracking data) into the texture space of the 3D model
3. Additively blend a grayscale Gaussian into the current gaze map texture, which is initially transparent. The Gaussian is scaled and positioned based upon a quadrilateral formed by the ray intersection points.
4. Map the additively blended textures to a heat scale – a 1D array of RGB values that visually appear "hotter" as the array index.

In our specific implementation, the gaze maps are alpha blended with underlying textured machine geometry. For example, the machine shown in figure 9 is a textured 3D model. However, gaze mapping could be extended to a see through display. If the registered 3D machine model was not rendered, then the gaze maps could be blended with a real-time video stream instead.

Although preprocessing time increases based on the number of data points, the preprocessing step must only be performed once. After the gaze maps are generated, they are written to textures, which can be stored on a hard disk for future runs of the application. This texture-based approach ensures that the amount of geometry does not increase since there is only need for the one 3D model. This allows the gaze maps to be rendered at an interactive rate (e.g. 30-60 fps, depending on hardware).

7.2 Markov model of class interaction

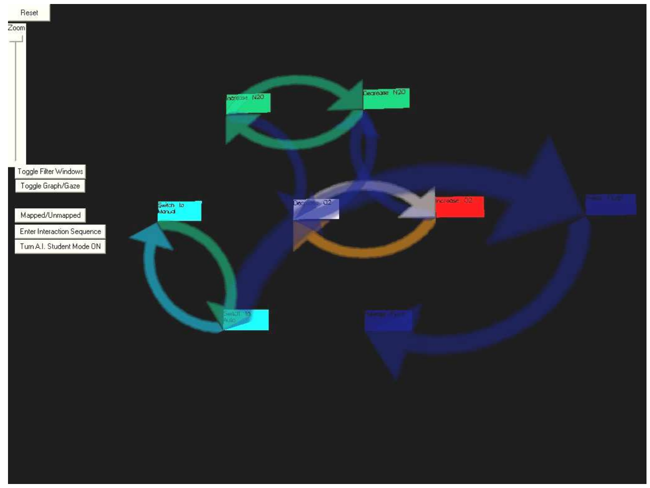

Figure 10. A heat-mapped (on frequency of interaction), directed graph of aggregate student interaction.

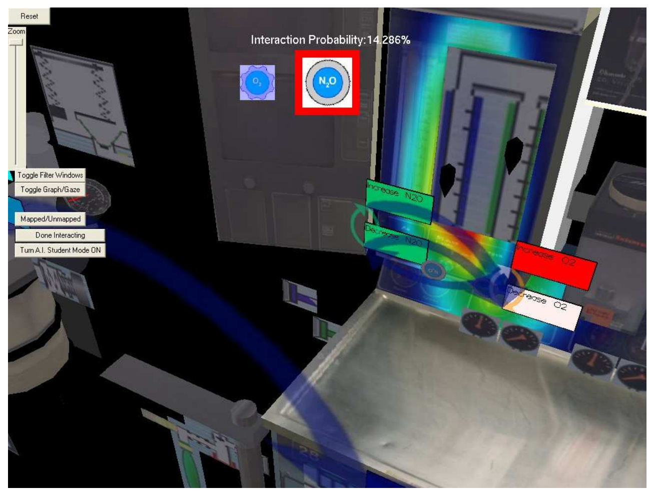

Figure 11. The interaction graph is collocated with the machine. Educators can test the probability of interaction sequences, highlighted by the icons at the top.

Trends in student interaction are important to improving educators' pedagogical approaches. This type of information is useful in determining whether students unknowingly perform interactions that are potentially harmful to a patient (e.g., over inflating the lungs with the oxygen flush valve). If the educator is able to isolate such a trend, then they can adjust their lesson plans accordingly. To meet this need, AAMVID-E aggregates and visualizes the interactions of an entire class of students

7.2.1 Implementation

Each student's interaction event chain (explained in section 5.1.3) is integrated into a simple Markov model [20]. A Markov model can be represented as a directed graph in which each arc has a probability associated with it. For a given node, all of the arc weights stemming from that node add up to 1. When traversing this graph as in a simulation, the arc weights represent the probability that a subsequent node will be visited. For example, a set of user logs contains a finite set of discrete interaction events. These events form the nodes of the directed graph. The sequence of events forms the arcs of the graph and the frequency of these sequences determines the weights on the arcs. Based upon the sequences and frequencies of multiple users' events, we can generate a probability (e.g. the percentage of students that performed the sequence) that a specific sequence of events will occur. These probabilities are the basis for the resulting Markov model.

Given such a model, educators can generate the probability that a student in the class will first increase the N_2O and second decrease the N_2O. This data is visualized as a directed graph (figure 10), which can be collocated with the anesthesia machine and visualized using the magic lens (figure 11). To interact with the interaction model, instructors press buttons and turn knobs on the machine in an order of their choosing. That is, by interacting with the machine, the educators traverse the directed graph of possible interactions. Then the model generates the probability that a student in the class would perform that sequence of actions.

7.2.2 Student A.I. Mode

The Markov model can also be used to drive the simulation of a "representative student". If the educator turns on the Student A.I. mode, the system will autonomously update the abstract simulation with interaction events (e.g. turning a virtual knob) based upon the Markov model of class interaction. Interaction sequences that are more probable will occur more often. This allows the educators to observe common interactions in class performance.

7.3 Data Filtering

For educators to more effectively identify class trends, it is helpful to be able to filter the data based on certain parameters such as class performance or standardized test results. To meet this need AAMVID-E allows educators to interactively filter the data based on parameters that the educator defines before runtime. For example, if the educator wanted to only visualize the gaze data of students with low spatial cognition, they can enter spatial ability test values for each student in the aggregate log files. At runtime, the expert can interactively manipulate sliders to select the range of spatial ability to visualize (figure 9). AAMVID-E's filtering allows educators to investigate how parameters, such as spatial cognition or standardized test scores, affect gaze and interaction. This interactive filtering allows educators to more effectively identify trends and outliers in the class.

8 Expert Evaluation of AAMVID-E

To evaluate the potential benefits of collocated AAR for educators, three experts in anesthesia education informally assessed the AAMVID-E. One expert was Dr. Samsun Lampotang – anesthesia education expert, inventor of the VAM, and co-author of this paper. The second expert was David Lizdas – Anesthesia Machine Expert, anesthesia simulation programming expert (programmed the VAM). The final expert was Nikolaus Gravenstein, M.D. – Professor and Chair of the Anesthesiology Department at the University of Florida. These three experts performed an evaluation by using AAMVID-E to visualize and interact with the aggregate training data obtained from the 19 AAMVID-S study participants.

8.1 Evaluation Procedure

Each expert evaluated the system individually. Each expert was first shown AAMVID-S. Then they were shown all the features of AAMVID-E and were asked to interact with it. Afterwards, each expert was interviewed and prompted to elaborate on several questions to determine usability, usefulness, and possible future directions of AAMVID. The questions are as follows:

1. What kinds of class trends are hard to identify?
2. Do you think AAMVID-E could help identify trends in class performance that you could not identify with your current assessment tools?
3. Would you prefer the MR-based version, a desktop version, or both for future reviews?
4. What would you like to see done differently in the future – e.g. visualizations, interfaces, filters?

8.2 Discussion

Question 1: Class trends? The experts' answers to this question suggest that educators need to be able to identify student misconceptions. Further, they need to understand *why* students have these misconceptions. To understand this, they are very interested in probing the thought processes of their students that cause the development of incorrect procedural skills (such as performing a sequence of actions in the wrong order). This understanding would enable educators to change their teaching methods and address the misconceptions in training, thereby improving training overall.

Question 2: Can AAMVID help identify trends that you could not identify before with current assessment tools? All of the experts answered yes to this question. They explained that the gaze data visualization coupled with the interaction sequence visualizations gives them a better understanding of the thought processes of students. Their impressions are summed up in the following quote:

> "[AAMVID-E] really gives us a new tool that we haven't had before, which is really getting a bit closer to seeing what [the students] are thinking." – Lampotang

Question 3: MR vs. desktop? We asked the experts if they would prefer the MR-based version or a desktop version. The experts noted that they would prefer both desktop and the MR versions. For convenience, (and because the lens can be cumbersome at times) they would like to use a desktop version for personal review – to visualize the data in their office or on their own computer. They would use the MR version for external review – to (1) perform an instructor-assisted AAR with a student (using AAMVID-S) (2) visualize the data for non-educators (such as anesthesia machine engineers) and (3) physically interact with the machine to manipulate the data. This highlights the advantages of MR-based collocated AAR for both visualization and interaction.

The desktop version of AAMVID is a 3D graphics application that is controlled with a keyboard and mouse. The gaze maps and interaction graphs are still visible and interactive, but the visualization and interaction takes place on a desktop computer, rather than on the magic lens in the context of the anesthesia machine.

Question 4: Future directions? The experts conceived other general uses for AAMVID-E in various domains. For example, they would like to use AAVMID-E in the future to visualize the economy of motion. That is, experts (medical and non-medical) are highly efficient in their interactions whereas novices might fumble or take more time between interactions. Based upon this economy of motion, educators would like to be able to track and visualize a novice's progress as more expertise is gained. AAMVID-E currently only visualizes frequencies and sequences of interaction and does not take into account this economy of motion. In the future, we hope to incorporate this aspect.

Dr. Gravenstein was specifically interested in applying collocated AAR to enhance the assessment of other training applications outside of anesthesia, such as surgery. His comments highlight the generalizability of AAMVID-E and collocated AAR:

> "You are presenting us with a new way to look at this kind of stuff in our weird environment. And the application isn't unique to our environment; the application is really in any environment where there are degrees of ability – especially where there are lots of steps and complexities that you have to sort out." – Gravenstein

9 CONCLUSIONS

We proposed the idea of collocated AAR using MR. MR-based collocated AAR augments the traditional AAR process by (1) allowing a user-controlled egocentric viewpoint, (2) overlaying virtual information that enhances learning (i.e. abstract simulation and automatic annotation of interaction events), and (3) collocating multiple training experiences in situ with the real training area (i.e. collocating one's own previous experience, an expert's previous experience, and current real-time experience).

The main challenges to MR are how to collocate multiple past experiences and the current experience with respect to time, interaction, and visualization. Our approach to addressing these challenges is exemplified with AAMVID – a MR-based system for collocated AAR in anesthesia education. To evaluate the system's approach to collocated AAR, both students and educators evaluated AAMVID. Results suggest that: (1) collocated AAR is a viable type of AAR that can effectively direct a student's attention and interaction and (2) collocated AAR offers educators novel assessment tools that, according to the educators, may help them to better understand the elusive thought processes of students.

For future work, we plan to investigate how collocated AAR could be applied to other domains outside of anesthesia (e.g. military domains, other medical domains, or other training domains that utilize AAR). To study this, we will conduct formal studies in multiple domains to determine the specific educational benefits of collocated AAR and evaluate our engineering approaches. We expect that MR may be a unique engineering solution for this application and further investigation of MR-based collocated AAR could potentially extend the known benefits and usage of MR.

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