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Adaptive instruction for medical training in the psychomotor domain

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Abstract

The adaptive instruction provided by Intelligent Tutoring Systems (ITSs) tailors direction, support, and feedback to enhance/maintain the learning needs (e.g., lack of knowledge or skill) of each individual. Today, ITSs are generally developed to support desktop training applications, with the most common domains involving cognitive problem solving tasks (e.g., mathematics and physics). In recent years, implementations of game-based tutors authored using the Generalized Intelligent Framework for Tutoring (GIFT), an open-source tutoring architecture, provided tailored training experiences for military tasks through desktop applications (e.g., games including Virtual Battlespace and Virtual Medic). However, these game-based desktop tutors have also been limited to adaptive instruction for cognitive tasks (e.g., problem solving and decision-making). The military requires adaptive instruction to extend beyond the desktop to be compatible with the physical nature of many tasks performed by soldiers, sailors, and airmen. This article examines how commercial sensor technologies might be adapted to work with GIFT and support tailored computer-guided instruction in the psychomotor domain for a military medical training task, specifically hemorrhage control. Toward this goal, we evaluated the usability and system features of commercial smart glasses and pressure-sensing technologies. Smart glasses were selected as the focus of this study over handheld mobile devices in order to promote a hands-free experience during the training of hemorrhage-control tasks on a mannequin. Pressure sensors were selected to provide direct measures of effectiveness during the application of tourniquets and pressure bandages. Each set of technologies (smart glasses and pressure sensors) was evaluated not with respect to each other, but with respect to their capabilities to support adaptive instruction *in the wild* at the learner's point-of-need and criteria based on established usability heuristics. Instruction in the wild is training provided in an environment outside the classroom and areas where tracking and sensing infrastructure are available (e.g., deployed areas of operation). We examined a wide range of features and capabilities, and evaluated their compatibility with the hemorrhage-control task, to answer the following question: what system design features (e.g., usability and interaction) are needed to support adaptive instruction for this individual psychomotor task at the point-of-need in locations where no formal training infrastructure is available?

Keywords

Adaptive instruction, Intelligent Tutoring Systems, psychomotor domain, smart glasses, pressure-sensing technologies, hemorrhage control

1. Introduction

Intelligent Tutoring Systems (ITSs) provide adaptive training and educational experiences where the instruction is tailored to support the specific needs of an individual learner or a team of learners.[1] ITSs are generally authored to support adaptive desktop training applications, with the most common domains involve cognitive problem solving tasks in mathematics and physics[2] or related user

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interfaces.[3,4] In recent years, implementations of game-based tutors (e.g., the reconnaissance training task in Virtual Battlespace and combat casualty care training in VMedic) using the Generalized Intelligent Framework for Tutoring (GIFT),[5–7] an open-source tutoring architecture demonstrated the efficacy of game-based tutors[8] and task domains beyond mathematics and physics. However, these tasks were also largely cognitive in nature and the military requires adaptive training tools for frequently performed psychomotor tasks (e.g., marksmanship, reconnaissance in urban environments, land navigation, and combat casualty care) involving both cognitive and physical aspects and occurring outside of locations with formal training infrastructure (e.g., the Joint Readiness Training Center). Specifically, we chose hemorrhage control, a combat casualty care task.

In order to support effective adaptive instruction for hemorrhage control at the point-of-need, this article examines which commercial smart glass and pressure-sensing features are critical to support the adaptive instruction of this psychomotor task. Adaptive instructional methods tailor training experiences based on the learning needs of each individual. The goal of adaptive tutors is to optimize learning, performance, and retention, and effectively transfer knowledge and skills to other domains, tasks, and operational environments.

We evaluated the usability and system features of 10 commercial smart glasses, including Atheer One, CastAR, Epson Moverio BT-200, GlassUp, Google Glass, LaForge Icis, Laster See-Through, Meta Space Glasses, Optinvent ORA-S, and Vuzix M-100 (Figure 1). Smart glasses were selected as the focus of this study over other augmentation technologies (e.g., handheld mobile devices) to promote a hands-free experience during training and align the actions in training more closely to the actions performed during hemorrhage-control tasks in the operational environment. Each set of smart glasses was evaluated not with respect to each other, but with respect to their capabilities to support adaptive instruction for the selected hemorrhage-control task at the learner's point-of-need.

We also evaluated the features of eight pressure sensors, which fall into four different classes. Our first class is piezo-resistive sensors, which use strain gauges to detect applied pressure. Resistance in the sensor increases as pressure deforms the material within the sensor. Our second class of sensors is capacitive sensors, which use a

Figure 1. Smart glasses evaluated.
(1: Atheer One; 2: CastAR; 3: Epson Moverio BT-200; 4: GlassUp; 5: Google Glass; 6: LaForge Icis; 7: Laster See-Through; 8: Meta Space Glasses; 9: Optinvent ORA-S; 10: Vuzix M-100.)

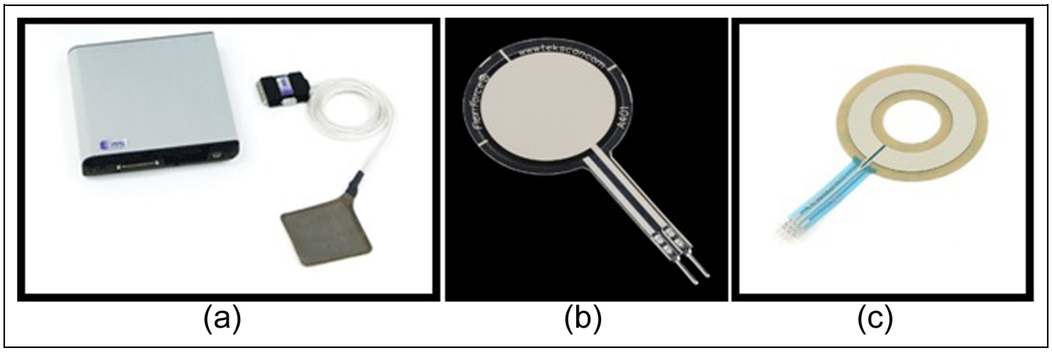

Figure 2. Sample of the pressure sensors evaluated: (a) TactArray (piezo-resistive); (b) FlexiForce (resistive); (c) Softpot (potentiometer).

diaphragm in combination with a pressure cavity to create a variable capacitor. This capacitor detects strain when pressure is applied to the diaphragm. The third class of pressure sensors we examined is piezo-electric, which includes electret film. Electret film is a dielectric material that can retain an electric charge or polarization similar to a magnet. Changes to the electric field of an electret can be measured and used to indicate changes in pressure. Finally, the fourth class of pressure-sensing technology examined in our study is force sensing, which includes potentiometers. Figure 2 shows a representative sample of the pressure sensors evaluated for this study.

We evaluated the range of smart glass and pressure-sensing features and examined their compatibility with the requirements for interaction and measures for our representative psychomotor task, hemorrhage control. Interactions and measures to support adaptive instruction include the following: presentation of content (visual and aural); presentation of feedback and support; acquisition of user behaviors (e.g., application of a tourniquet) to support feedback decisions by the tutor; assessment of critical tasks (e.g., sufficient pressure to control bleeding); assessment of learning, performance, and retention; and user control of media to augment cognition during training. The goal of this evaluation was to answer the following question: what system design features (e.g., usability, measurement, and interaction) are needed to support adaptive instruction for this individual psychomotor task at the point-of-need in locations where no formal training infrastructure is available?

1.1 Point-of-need training capability requirements

The military requires easily accessible, persistent, cost-effective, and low-overhead training environments.[9] A capability is needed to bring training to soldiers instead of soldiers going to fixed training locations. This point-of-need training capability should be easily distributed, web-based, and built upon an open-enterprise architecture in the cloud. Military training and educational opportunities should be available on demand anywhere and anytime. However, it should also be noted that the delivery mode (e.g., desktop computer, laptop computer, mobile device, or smart glasses) for adaptive training is critical in determining the limitations of the domain model and the scope and complexity of training tasks (e.g., how closely the actions performed in training the task align with performance of the task in the operational environment). For example, it may be extremely difficult to train all the complexities of a psychomotor task in a desktop computer mode.

The major connection between point-of-need training and domain modeling is the practicality of extending adaptive training beyond the desktop. Low-cost commercial tools (e.g., smart glasses and sensors) must be investigated to determine their suitability to support the comprehensive range of actions normally performed in the operational environment to promote the highest degree of transfer from training to operations. It is critical to discover methods to identify learner actions (classification), associate these actions with progress toward learning objectives (assessment), and provide effective feedback on learner actions to optimize deep learning.

The cloud architecture to support adaptive instruction will be required to operate with and without internet connectivity, depending on the location of the learner and their access to the network. For example, if a soldier decides to take a 2-hour training course while traveling and knows that internet connectivity will be intermittent in his location, he might decide to download the course to his device and take it offline. The architecture must be able to track the soldier's progress and upload results when connectivity is again available.

1.2 A representative military training task for adaptive instruction at the point-of-need

The representative military training task for adaptive training at the point-of-need we selected was hemorrhage control. We selected this task because it requires the use of both cognitive and physical skills outside of the traditional desktop applications and classroom environments in a psychomotor task domain where adaptive training techniques have not been previously applied. The hemorrhage-control task was also selected because it is commonly performed in the field and requires the learner to evaluate perceptual (visual and haptic) cues, exercise cognitive processes (problem solving and decision-making), and take actions (e.g., increase pressure on the wound or conduct a blood sweep).

According to Army training doctrine regarding tactical combat casualty care,[10] the hemorrhage-control task involves the treatment of wounds involving loss of blood, including extremity, junctional, and torso wounding. For the purposes of this task breakdown, a severe lower-leg hemorrhage with a rapid rate of blood loss is the chosen injury. For such an injury, hemorrhage control begins when the care provider, a Combat Medic or Combat Life Saver, takes precautions regarding body substance isolation, primarily the use of gloves. The care provider then removes clothing and debris to expose the wound and fully assess the severity of the injury and blood loss. If possible, a care provider applies pressure above the wound to slow blood loss during treatment. Tourniquet application is the immediate treatment to reduce/eliminate blood loss, using the Combat Application Tourniquet (Figure 3).

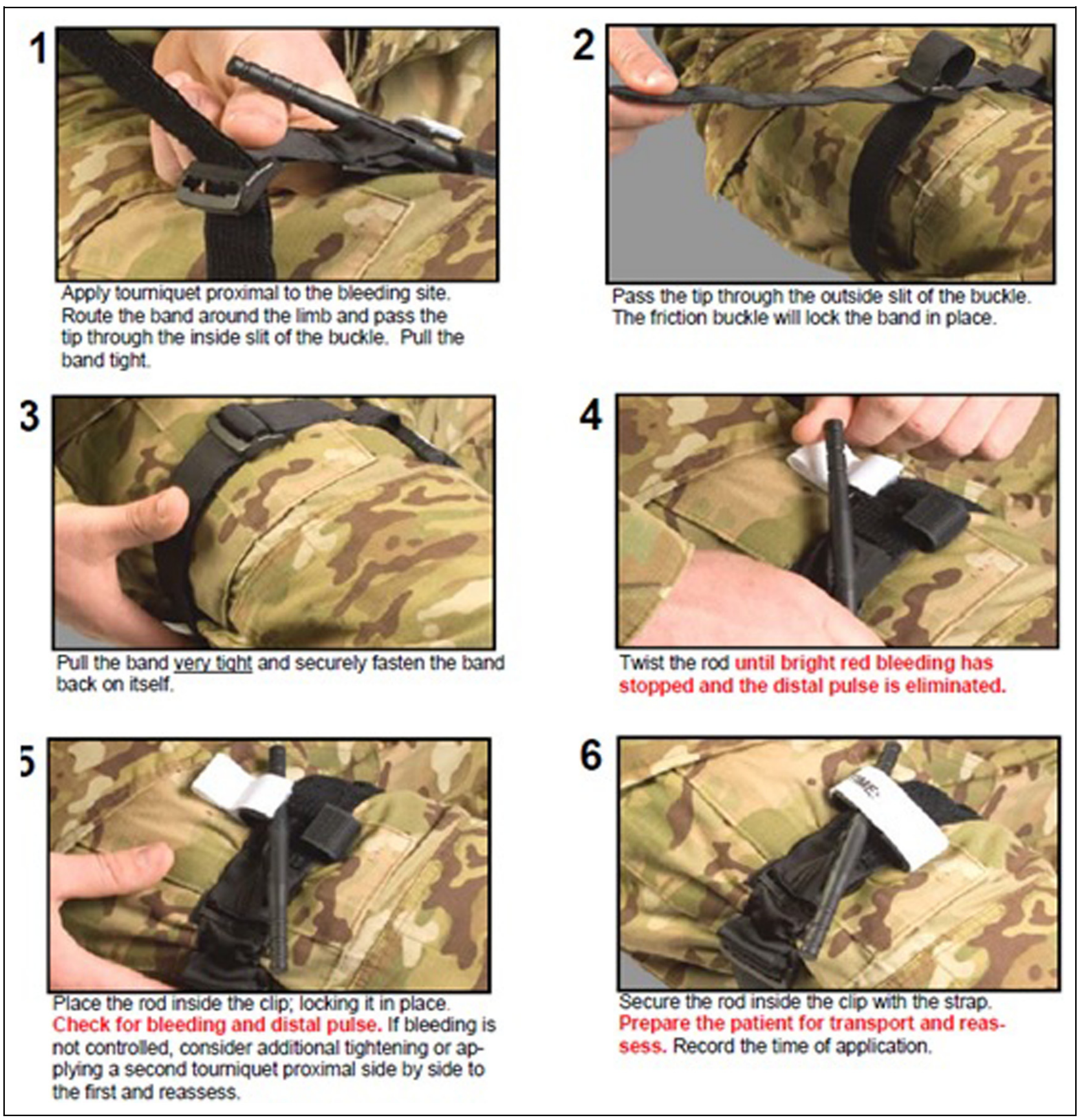

Figure 3. Representative Steps and measures for the hemorrhage-control task – tourniquet application.[11]

The care provider applies the tourniquet 2–3'' above the wound. The care provider applies the tourniquet tightly using the Velcro strap, and twists the windlass until bleeding stops. Once visible bleeding stops, the care provider secures the windlass and marks the casualty with a ''T'' and the time of application. The care provider performs a blood sweep of the body to identify any other injuries requiring treatment. If other wounds are found, the provider treats these prior to returning to the leg wound. If no additional injuries are found, the provider applies an emergency bandage to the leg wound to minimize blood loss. With immediate treatment complete, the care provider monitors the vital measures of the casualty, including pulse rate, blood pressure, and respiratory rate. If needed, the care provider may insert an intravenous catheter and supply saline, blood products, or other fluids to further stabilize the patient. By this point, the care provider or squad leader calls in an evacuation request. During evacuation, the care provider monitors the patient and prepares them for patient handoff, which ends the hemorrhage-control task within tactical combat casualty care.

During a training event focused on hemorrhage control, learners receive didactic instruction to ensure basic understanding of the procedures. They may practice their skills in a virtual environment, such as TC3Sim[12] or Virtual Combat Medic.[13] Finally, students perform these procedures on part task trainers, medical mannequins, and during field exercises. Assessment of both virtual and live training uses psychomotor checklists and a set of metrics to determine a student's performance. The psychomotor checklist breaks down the hemorrhage-control task into a series of discrete steps, each with discriminators for proficiency. For example, the tourniquet task requires exposing the wound, correct positioning of the tourniquet, tightening using the windlass, securing the windlass, and marking the time on the casualty. Each of these comprises a necessary step in the overall tourniquet task, and an instructor assesses each step to determine student proficiency.

2. Methodology for usability evaluation

Adaptive systems (e.g., ITSs) provide one-to-one computer-guided learning experiences that are tailored to each individual learner's needs and capabilities. The application of smart glass and pressure-sensing technologies to adaptive instruction is new, so we began by identifying criteria in the context of our representative military task, hemorrhage control, and usability criteria based largely on Nielsen's usability heuristics,[14] which are summarized below.

2.1 Criterion: information availability and visibility

The system should always keep users informed about what is going on, through appropriate feedback within a reasonable amount of time to allow for effective user response. The system should use visuals, alerts, and icons that are simple and consistent. Only important information should be displayed. Examples of system status indicators relevant to our task are battery meters, dashboards, and mouse-over screen tips for system objects. Menus should not contain information that is irrelevant or rarely needed. Every extra unit of extraneous information in a menu competes with the relevant units of information and diminishes their relative visibility. Ideally, smart glasses supporting tutoring at the point-of-need must be able to support the development of new menus and interfaces to allow user interaction in a variety of domains. They must also be able to provide information to the user while not obscuring the user's view of the environment (e.g., the casualty).

For our hemorrhage-control task, content presented via smart glasses may be used to augment the learner's memory and reduce cognitive workload through prompts while training. For example, the user might be prompted for information about the location of a tourniquet in relationship to a wound prior to applying the tourniquet. Interactive dialogue with the tutor will allow the learner to recognize many errors on their own. For more detail on this interaction, see Section 2.4.

2.2 Criterion: consistent user interfaces and standards

The system's user interfaces should be consistent with the users' language and use terms, phrases, and concepts that are familiar to the user. The system interface should be consistent with established norms for the task(s) to be accomplished (e.g., land navigation). Real-world conventions should be used to make information appear in a natural and logical order. The system should avoid the use of system-specific terms, phrases, and concepts in order to reduce cognitive workload and promote automaticity as the learner progresses with training. Users should not have to wonder whether different words, situations, or actions mean the same thing. User interfaces should maintain consistent language across menus.

For example, in our hemorrhage-control task, common terms used are tourniquet, windlass, hemostatic agent, coagulation, and hypovolemic shock. For example, the tutor should always use proper names of instruments and components, rather than a descriptive synonym, such as using tightening rod of the tourniquet rather than the term windlass.[15] In addition, physiological processes and responses should use scientifically appropriate terminology. Terms related to blood clotting should be clear and concise; coagulation is the correct term for the process of blood clotting, and a hemostatic agent helps to speed up that process.[16] Hypovolemic shock occurs when severe blood and fluid loss make the heart unable to pump enough blood to the body.[17] Using synonyms or colloquialisms for these terms may be confusing to the learner and detract from efficient task execution during the planning phase. Prior to training and when necessary during training, it is important to assess the learner's knowledge of common terms to ensure they understand and can recall these common terms. Therefore, adaptive instruction provided via smart glasses should be able to deliver and score assessments of knowledge and provide appropriate feedback, support, and remediation during planning and instruction.

2.3 Criterion: user control

Users, especially novice users, may choose system functions by mistake. The system should support *back* and *home* functions along with *undo* and *redo* functions to allow users to quickly escape when they select a function by mistake. For example, when assessing tourniquet application for our hemorrhage-control task, the user should be able to change their decision quickly and easily based on visual and haptic feedback if bleeding continues after completing tourniquet treatment. If a user does not notice the visual or haptic cues indicating this mistake, a tutor may provide cues to help a user recognize and correct the mistake.

2.4 Criterion: error recognition and prevention

In most cases, we want the system be able to recognize errors and provide error messages. These messages should be expressed in plain language (no codes), precisely indicate the problem, and constructively suggest a solution. However, while good error messages are an important element of adaptive system design, error prevention may be more important in some cases. It may not be efficient to allow incorrect treatment of a wound, such as missing an important secondary wound, resulting in patient death. Ideally, we would like the user to discover these errors on their own during planning through a reflective discourse with the tutor rather than just allowing the system to identify the error and suggesting an alternative route. The following is a simplified example of a potential dialog for novice training to gain competency in hemorrhage control.

Tutor: ''Let's stop here to analyze your current treatment… tell me step-by-step what you did.'' < reflective prompt >

User: ''I have removed the clothing and debris, and assessed the wound. I've used proper body substance isolation and began applying my tourniquet, and I am ready to tighten the windlass.''

Tutor: ''Please identify the location of the tourniquet in relationship to the wound.'' < request for user input >

User: ''I am applying it approximately 5'' above the wound. I realize I should apply it closer to the wound, in the range of 2–3'' above the wound. I will reposition the tourniquet now.''

The reflective discourse continues as the user evaluates the treatment based on their new knowledge. Once the tourniquet treatment is completed correctly, the tutor will guide the user through the next phases of hemorrhage control. Again, this guidance is provided indirectly as the user veers significantly off course:

User: ''I have completed tourniquet application. I am beginning to bandage the wound.''

Tutor: ''Analysis of your tourniquet application shows blood loss has been controlled, indicating correct tourniquet placement.'' < feedback > Are there any other injuries present?'' < reflective prompt >

User: ''I don't know. I should have conducted a blood sweep, to determine if there are other injuries requiring treatment. I will conduct a blood sweep now.''

Tutor: ''Good, what did the blood sweep indicate?'' < request for user input >

User: ''I found a wound to the abdomen that I will now bandage, and then proceed to bandage the leg wound.''

Tutor: ''Excellent. Secondary injuries can be difficult to notice without a thorough blood sweep.'' < feedback >

2.5 Criterion: comfort, durability, ease of use, and flexibility

As the hardware element of the adaptive tutoring system for psychomotor tasks, smart glasses should be comfortable to wear over the time required to execute the training task. Lightweight, durable materials that can be worn in varying weather and lighting conditions are desirable for smart glasses. In order to minimize the user's memory load, the system should make objects, actions, and options visible to the user so they do not have to remember where to find them. The user should not have to remember information from one part of the user interface to another. Instructions for use of the system should be visible or easily retrievable whenever appropriate. In the case of our hemorrhage-control task, we might want the underlying anatomical structures to appear in the heads-up display based on a voice command in order to keep the user's hands free for other tasks; for example, the underlying arteries and bone structure surrounding the injury. Even though it is better if the system can be used without documentation, it may be necessary to provide help and documentation on demand. Documentation should be easy to search, and focused on the objects, actions, and options available to the user at the time of the query. The user interface should be flexible and allow for accelerated actions (e.g., shortcuts) for more advanced users to speed up interaction. The smart glass interface should support both inexperienced and experienced users and allow users to tailor frequent actions.

Unlike surgical cricothyrotomy, which requires not only anatomical landmark identification but an invasive incision, tourniquet application is not an ''invasive'' procedure. Thus, pressure sensors that can measure tourniquet application and provide feedback to assess blood loss can reasonably be expected to last significantly longer than sensors that measure surgical cricothyrotomies. However, meantime between failure (MTBF) testing has not yet been performed for either class of sensor as part of this study.

3. Results of system feature and usability heuristics evaluation

The method used for this evaluation included a review of the salient characteristics of both smart glasses and pressure sensors. The heuristic evaluation process for the smart glass features was reproduced from Sottilare and LaViola,[18] by permission of the National Training & Simulation Association, and more broadly applied to both smart glasses and pressure sensors for the medical hemorrhage-control task in lieu of Sottilare and LaViola's[18] previously studied land navigation task. This method analyzed smart glass and pressure sensor hardware with respect to their ability to meet the perceptual needs of the learner and their ability to support the interaction required to tutor the medical hemorrhage-control task. Tables 1 and 2 provide system specifications and features for the 10 smart glasses evaluated as part of this study. Table 3 includes system specifications and features for the eight pressure sensors evaluated as part of this study.

3.1 Smart glass features and specifications: display, battery life, weight comfort, and software development kits

Table 1 specifications include the following: what the images are able to be projected on (glasses or real-world surfaces in the environment); whether information is displayed within the learner's field of vision or outside (i.e., side, above, or below); the display type (e.g., two- or three-dimensional); the display resolution; battery life; field of view (FOV); weight (grams); and whether a

Table 1. Smart glass system specifications (part 1).[18]

Smart glass	System specifications							
	Project images to	Display in field of vision	Display type	Display resolution	Battery life	Diagonal FOV	Weight	Developer kit?
Atheer One	Glasses	Within	Color, 3D stereo	1024 × 768	6 hours	65 degrees binocular	70 g	Not public
CastAR	Glasses and real world	Within	Color, 3D stereo	1280 × 720	1 day	65 degrees binocular	100 g	Yes
Epson Moverio BT-200	Glasses	Within	Color, 2D and 3D stereo	960 × 540	6 hours	23 degrees binocular	88 g (glasses) + 124 g (controller)	Yes
GlassUp	Glasses	Side	Monochrome 2D	320 × 240	1 day	NA	65 g	Yes
GoogleGlass	Glasses	Above	Color, 2D	640 × 360	1 day	14 degrees monocular	50 g	Yes
LaForge Icis	Glasses	Side	Color, 2D	800 × 600	6 hours	NA	80 g	Yes
Laster SeeThrough	Glasses	Within	Color, 2D	800 × 600	6–8 hours	40 degrees monocular	55 g	Yes
Meta Space Glasses	Glasses	Within	Color, 3D	960 × 540	32 hours via pocket computer	23–35 degrees	180 g (glasses only)	Yes
Optinvent ORA-S	Glasses	Within and side	Color, 3D	640 × 480	4–8 hours	24 degrees monocular	80 g	Yes
Vuzix M-100	Glasses	Within	Color, 2D	428 × 240	6 hours	Monocular	85 g	Yes

FOV: field of view; 2D: two-dimensional; 3D: three dimensional.

Table 2. Smart glass system specifications (part 2).[18]

Smart glass	System specifications						
	CPU	Memory and storage	Connectivity	Photos	Videos	Features	Sensors
Atheer One	Via smart phone (Android)	Provided by smart phone	Wired to Smartphone	8 MP	NA	Gesture support	Gyroscope, accelerometer, compass, proximity sensor, capacitive touch sensor, ambient light sensor, GPS
CastAR	Via smart phone	Provided by connected devices	Wi-Fi, Bluetooth	NA	NA	Wand controller	120 Hz absolute tracking with sub millimeter precision; 1000 Hz inertial tracking
Epson Moverio BT-200	Onboard	1 GB RAM; 8 GB (32 GB with SD card)	Wi-Fi, Bluetooth, and via Android device	VGA	VGA	Touchpad (on controller), Dolby Digital plus sound, projectors	Camera, GPS, compass, gyroscope, accelerometer, microphone
GlassUp	Via smart phone	NA	Bluetooth	NA	NA	Touchpad on glasses, real-time information feeds (read-only)	accelerometer, compass, ambient light sensor, precision altimeter
GoogleGlass	Onboard	1–2 GB RAM; 16 GB	Wi-Fi, Bluetooth	5 MP	720p	Touchpad, voice control	Camera, accelerometer, gyroscope, magnetometer, ambient light sensor, and proximity sensor
LaForge Icis	Onboard	1 GB RAM	Bluetooth and via Android device	5 MP	720p	IambicFLO™ directional speaker	Gyroscope, accelerometer, touchpad
Laster SeeThrough	Via smart phone	Provided by connected devices	Bluetooth	NA	NA	Text, email, phone, music	GPS, 10 DOFs head tracker, gyroscope, accelerometers, compass
Meta Space Glasses	Via pocket computer	4 GB RAM; 128 GB (via pocket computer)	Wi-Fi, Bluetooth	5 MP	720p	Dolby 3D surround sound, 2 microphones	3D time of flight camera, color camera, 9-axis Integrated Motion Unit: accelerometer, gyroscope and compass
Optinvent ORA-S	Onboard	1 GB RAM; 4 GB	Wi-Fi, Bluetooth	5 MP	1080p	Touchpad, voice control, control buttons, speaker	Camera, 9-axis motion sensor, ambient light sensor, proximity sensor, GPS
Vuzix M-100	Onboard	1 GB RAM; 4 GB	Wi-Fi, Bluetooth	5 MP	1080p	4 control buttons, remote control app, voice navigation and gestures	3 DOF gesture engine (L/R,U/D,N/F), ambient light sensor, GPS, proximity sensor, 3 DOF head tracking, 3-axis gyro, 3-axis accelerometer, and 3-axis mag/ integrated compass

GPS: global positioning system; DOF: degree of freedom; 3D: three-dimensional.

software developer kit is available. A discussion of the specifications related to Table 1 follow, including feature descriptions, their range, their relationship to usability heuristics, and their potential impact on the training of our hemorrhage-control task.

3.1.1 Display features. Display features include display modes, presentation of information in the field of the user's vision, display type, resolution, and diagonal FOV per display. Projection modes may either mirror the displays of tethered devices (e.g., smart phones) or support independent menus. Virtual images may be within or outside the field of the user's vision (i.e., above, below, or to the side of the user's field of vision) within the smart glasses or projected onto an external surface.

Related to the usability heuristic, *information displays and visibility* is the need to keep users informed about the system status. While it is important to have information about battery status and other system data available to the user, placing information directly in the view of the user at all times could cause safety issues by occluding all or part of the real-world view. In support of a hemorrhage-control task, we recommend a schema to place information to the side, above or below the user's vision unless the information is an alarm or other time critical information. The user should also be able to move information and images into and out of their field of vision at will. Of the 10 smart glasses evaluated, only the ORA-S provided the option to present data both within and below the user's field of vision. An adaptive tutor could provide alerts through text messages to Bluetooth-enabled smart glasses. The location of text alerts could be displayed outside the user's field of vision and moved within the field of vision to gain attention. A text message could also be translated to a voice message to eliminate clutter and reduce cognitive overload by providing feedback through a second sensory channel.

Display types were primarily color and supported two-dimensional projections, which is suitable to provide illustrations and augmented labels for assisting during treatment procedures. However, the size and detail of illustrations and other visual aids available to the user may be limited by the display resolution, which varied widely, but was as low as 320×240 pixels. Given diagonal resolution as low as 14 degrees, FOV may also be a limiting factor in presenting anything more than simple two-dimensional images without interfering with the user's field of vision of the real world.

3.1.2 Battery life. Battery life for the evaluated smart glasses ranged from 4 to 32 hours. From a practical perspective, the learner in our hemorrhage-control task should not have to worry about the battery life of their smart glasses during adaptive training experiences. We recommend the battery in our notional adaptive training system provide at least one day of uninterrupted power, provide unobtrusive methods for recharging the battery (e.g., solar battery charger), or provide additional battery storage (e.g., Meta Space Glasses pocket computer) for extended exercises.

3.1.3 Weight and comfort. When we discuss system weight, we are primarily talking about user comfort. The glasses evaluated ranged from very light (50 g or about 1.8 oz) to light (180 g or about 6.3 oz). A review of these glasses reveals that they can be worn for long periods of time (over 4 hours) without significant discomfort. Of consideration is how the glasses rest on the bridge of the nose and the ears. Binocular glasses tend to balance the weight more evenly across the nose and ears, and are therefore recommended over monocular models. Another consideration is whether the glasses move around significantly when the user runs, climbs, or changes direction or posture.

3.1.4 Software development kits. The usability of smart glass-based ITSs largely depends on the ability of the user to interact with the system. Nearly all of the glass sets reviewed had a compatible, publicly available software development kit (SDK) to support authoring of unique applications. While this might have minimal impact on our relatively simple hemorrhage-control task, it is desirable to be able to present information to the user in a variety of formats during the adaptive training process, and this may require the development of new menus and user interfaces. For example, it might be necessary to develop an interface for a tutoring architecture (e.g., GIFT) to support interaction between the learner and the ITS (e.g., questions by the user or feedback from the tutor).

3.2 Smart glass features and specifications: processing power, connectivity, camera, and sensor features for smart glasses

Table 2 specifications include information about the following: onboard computing power, memory, and storage; wireless connectivity; photo and video capabilities; sensors; and other interface features (e.g., touch pads and wands). A discussion of the specifications related to Table 2 follows, including feature descriptions, their range, their relationship to usability heuristics, and their potential impact on training our hemorrhage-control task.

3.2.1 Processing power and connectivity. Some level of onboard processing, memory, and data storage are a must for supporting data manipulation, learner state classification based on behavior and/or physiological measures, and archiving of learner actions and states for after-action-review (AAR). Real-time assessment of learner states is critical to real-time feedback and the management of adaptive instruction per the learning effect model.[19,20] The ability to store/retrieve patient vital measures and performance metrics, such as treatment time and total blood loss, on demand is critical to our hemorrhage-control task.

Half of the smart glasses reviewed provided onboard processing power, while the remaining glasses offloaded processor tasks to a smart phone or other device (e.g., Android tablet or pocket computer) via Bluetooth. Wi-Fi-enabled devices were also common among the glass sets evaluated, but unlikely to be useful for our hemorrhage-control task in the wild based on the potential low availability of Wi-Fi in some locations. The processing power and connectivity features of these devices directly affect the effectiveness of smart glasses as a mechanism to support adaptive training at the point-of-need.

3.2.2 Camera and sensors. Seven of the 10 smart glasses included a camera and six of 10 included video. The capture and display photos and video could support data collection for an automated AAR provided via the smart glasses. Significant artificial intelligence (AI) would be needed to support individualized, automated AARs, but the data capture could be driven by interaction between the computer-based tutor and the learner. For example, the camera could be used to compare the user's current placement of a tourniquet on the wound to an ideal placement. Common errors by learners attempting to control bleeding could also be captured on video for display during the AAR.

While useful for some tasks, global positioning systems (GPSs), compasses, and inertial tracking capabilities do not support critical measures for our hemorrhage-control task. Voice controls may be important to support improved usability and hands-free interaction during training. The user's voice can be used to activate menus and support easier data input (e.g., text input) during training. Sensors to support gesture recognition for pointing and selecting from menus may also reduce the user's cognitive workload by closely mirroring actions needed to complete the task in the operational environment during training.

A few of the systems reviewed included touch pads on the glasses (i.e., Glassup, GoogleGlass, and Optinvent ORA-S). The Epson Moverio provided a separate touchpad. Each of these devices provided limited menu navigation capabilities, were awkward to operate, and seem to be less much less efficient than voice control. Much the same as texting while driving is distracting and potentially dangerous, we found that using touch pads external to the smart glasses tended to draw the user's attention away from the display during input and could result in safety issues during training. Finally, the ambient light sensor is critical to adjusting displays during the operation of most of the smart glasses we reviewed.

3.3 Features for pressure-sensing technologies

Table 3 specifications include information about the following: pressure range, sensor elements, speed, and cost of pressure sensors. A discussion of the specifications related to Table 3 follows, including feature descriptions, their range, their relationship to usability heuristics, and their potential impact on training our hemorrhage-control task.

We examined the attributes of the four classes of pressure sensors noted previously: piezo-resistive (measure changes in the electrical resistance of a material), capacitive sensors (use a diaphragm with a pressure cavity), piezo-electric (measure changes in electric field of material), and force sensing (e.g., potentiometers). Converting all units in Table 3 to mm Hg resulted in the following pressure ranges for each class of sensors:

- piezo-resistive sensors (0.5–10,343 mm Hg);
- capacitive (0.0–10,343 mm Hg);
- piezo-electric (no pressure data available);
- force sensing (0.16–15.5 mm Hg).

Table 3. Sample system specifications for popular pressure sensors.

Sensor name	Manufacturer	Type	Pressure/force range	Speed	Cost
Tactilus	Sensor Product	Piezo-resistive	0.01–200 psi	1 KHz	US$50
Flexiforce	Tekscan	Resistive	4.4–111 N	6 KHz	US$34–78
Pliance	Novel Electronics Inc	Capacitive	0–30 psi	Not available	Not available[a]
S-series	Emfit	Electret film	Not available	20KHz	~US$14.75
PressureSensor	Virtuabotics	Resistive	0.2–20 N	4 Hz	US$7.95
FSR 4Zone	Interlink Electronics	Resistive	–20 N	> 100 KHz	US$11
Softpot	Spectra Symbol Inc	Resistance-potentiometer	No pressure/force. Location only	Not available[b]	US$10–20
Digitacts/ TactArray	Pressure Profile Systems	Capacitive	0–200 psi	10 Hz	US$9500

[a]Single units not sold in the USA. Available in Germany.
[b]Speed is a function of device sampling for the sensors more than the sensor itself.

To stop bleeding effectively, pressure must exceed limb occlusion pressure (LOC).[21] For thigh tourniquet pressure, surgeons reported that they most commonly used 300–350 mm Hg of force to reach LOC.[22] Given this high amount of pressure, only the piezo-resistive and capacitive sensors are successful candidates to support our hemorrhage-control task. Specifically, the capacitive sensor with a range of 0–30 psi meets the range and tolerance measures required.

4. Recommendations and future research

The evaluation of the 10 commercial smart glasses and eight pressure sensors identified recommended best practices for adaptive tutoring in the wild for our hemorrhage-control task. For displays, we recommend the option to present data within and below the user's field of vision where the tutor and the user can move text and graphical data into the user's field of vision based on the criticality of the information. As in all portable systems, battery life was deemed critical for long-duration tasks (tasks exceeding the normal time for a training class; more than 1 hour) to keep the user from having to constantly focus on whether their battery will last through the training experience. Weight and comfort were identified as something already provided by commercial smart glasses, but we recommend maintaining the glasses at 50 g or less to maximize comfort over long-duration exercises. Tinted and prescription glasses are also recommended to support long wear in bright sunlight and for users who have corrected vision.

Connectivity via smart phone (Bluetooth) is recommended to allow for real-time interaction with the adaptive tutor and to support other service calls to the cloud (e.g., learner state classification algorithms). As a backup, onboard processing power is a must to support local classification of learner states (e.g., frustration, surprise, boredom). Cameras and sensors, especially GPS, can provide needed data to the adaptive tutor to assess the performance of the learner in real time in the wild. Finally, SDKs, while prevalent in commercial smart glasses, may not provide the flexibility needed to support presentation of all the training material and graphics needed to support psychomotor tasks in the wild. Additional evaluation is needed across several military psychomotor tasks to determine the true extent to which current SDKs can support presentation of training content to the learner.

Evaluating the sensor led to a balance of cost and features. For the task of tourniquet application, speed was not overly critical – sampling the sensors at a rate of 1 Hz is more than sufficient to determine when a student has applied a sensor. More sensitivity was likewise not as important; Hagenouw et al.[23] determined 260 mm Hg, or approximately 5 psi, was sufficient to stop arterial flow. Thus, paying more for sensors that detect very low pressures was wasteful. Likewise, most patient simulators replicate human arterial blood flow fairly realistically, and the pressure required to stop a manikin's arterial flow would also stop a human's arterial flow. With these factors in mind, the Softpot by Spectra Symbol was chosen as the initial sensor to test. While it does not measure pressure, it was fairly low cost and projected to be durable. Testing continues to determine whether it will be useful across a range of medical interventions.

5. Conclusions

Our evaluation of commercial smart glasses identified several capabilities that are necessary antecedents to adaptive tutoring in the wild. We examined a wide range of smart glass features and capabilities, and evaluated their compatibility with a representative military task, hemorrhage control, to answer the following question: what system design features (e.g., usability and interaction) are needed to support adaptive training for this individual psychomotor task so it can be taught anywhere, including in the wild?

Smart glasses were the technology of choice in lieu of smart phones, based on the need for hands-free operation to support psychomotor tasks (e.g., land navigation) where information exchange with the adaptive tutor could guide learning and present instructional content while still maintaining safe interaction with the real-world environment. This evaluation was not intended to compare and select a pair of smart glasses, but instead to provide an understanding of the range of available capabilities in order to operationalize requirements for adaptive tutoring in the wild. The evaluation was also conducted to provide identification of gaps where capabilities in commercial smart glasses could not currently support adaptive tutoring in the wild.

The results of our evaluation revealed strengths and weaknesses for all of the smart glasses examined. Not one provided the range of capabilities and usability required to support our candidate military task, hemorrhage control, but each possessed salient characteristics that could be used to drive requirements for future smart glass design to support the adaptive training of psychomotor tasks.

Clearly, for a hemorrhage-control task, display resolution is a critical factor and most of the devices analyzed do not have high enough resolution to represent the depth and severity of wounds when significant detail is required for treatment. The one pair of smart glasses that has reasonable resolution is the CastAR system. However, this device requires special retro-reflective material, which may make it impractical for use ''in the wild''. In addition, these smart glasses all have a relatively small FOV, which can be a problem when images need to be superimposed over a large range at any one time. All the devices do have

Figure 4. In the wild psychomotor tasks for medical, maintenance, and tactical planning.

a variety of different sensors that, when coupled together, can provide tracking at reasonable accuracy levels.[24] This represents a strength of the different smart glasses we examined.

The next step in exploring ITS-based instruction in the wild requires both improved hardware and software to support high-resolution displays with wide FOVs. Currently, proof of concept exploration of this area could be accomplished with a smart glass device such as the Meta Space Glasses, given that they have several sensors that may be used to properly acquire a three-dimensional scene in real time and to support simultaneous localization and mapping (SLAM)-based tracking.[25] Although the FOV is small, work is currently being done to expand the FOV. As an example, Maimone et al.[26] have developed a pair of smart glasses with a 100-degree FOV.

Another recommendation for future research is to explore other methods to improve display resolution and FOV by combining depth cameras and high-definition (HD) web cams with commodity head-mounted displays (HMDs), such as the Oculus Rift. This combination would support 1080p resolution at a 100-degree FOV. Of course, the device would be heavier than most smart glasses and would also need computational power greater than the amount supported by the smart glasses reviewed. Given hardware that is ''good enough'' to support proof of concept prototyping, further research involves the best way to present tutoring information to a trainee and to examine the most appropriate methods for having the trainee enter information into the ITS. There are a variety of different possibilities, including three-dimensional user interfaces, tablets, and voice communication. All of these methods need to be explored not only from a technological perspective, but also from a user experience and pedagogical perspective as well.

Our last recommendation for tutoring *psychomotor tasks* is to expand the number and type of tasks that might be included within our *in the wild* taxonomy. Our definition of in the wild pertains to locations where no formal training infrastructure is present. This definition opens up the possibilities that in the wild tutoring does not only include tasks performed in outdoor real-world locations, but might also include tasks performed indoors where there is no formal training infrastructure to provide immersive experiences or track individual trainee behaviors. These training tasks might include other medical tasks, land navigation, maintenance, or planning for tactical operations domains (Figure 4) where cognitive (thinking) processes and physical (doing) processes merge. Additional research is needed to explore the idiosyncrasies of these domains and to understand the interaction and usability needs for various classes of tasks.

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