Augmented Reality in Tactical Combat Casualty Care: Physiological Ramifications

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ABSTRACT

As augmented reality (AR) applications become more popular in industry and military training contexts, it is critical that these immersive platforms be designed and used with a clear understanding of their benefits and limitations. AR applications have significant potential to accelerate training timelines and improve operational performance as a result of their ability to present data in a more realistic and embodied context. However, physiological maladaptation following prolonged AR exposure is not only possible, but probable due to restricted field-of-view, vergence-accommodation conflicts, and other system anomalies. It is crucial for the scientific and research communities to fully understand and characterize the potential for and magnitude of physiological maladaptation imparted by AR systems. Since AR has been shown to produce less overtly incapacitating physiological symptoms (e.g., less nausea and more eyestrain) than its counterpart, virtual reality, it is likely users will stay in immersive AR environments longer, potentially causing more severe and persistent adverse outcomes. If extended exposure within AR systems produces adverse physiological effects, such as postural instability and cybersickness, these limitations may have implications on training effectiveness and operational safety. This study, consisting of 60 participants presents a comparison of postural sway, an objective indicator of cybersickness, between three types of AR systems. The study compared the Samsung AR Tablet to the HoloLens 1 to the Magic Leap One within the context of extended-duration (2 hour) AR training exposure, to determine what differences exist between these display types in terms of their physiological impact. Results from this experiment suggest that prolonged AR exposure resulted in habituation but not dual adaptation, as high levels of anterior posterior sway were seen post exposure. In the future it will be important to further quantify the adverse physiological effects associated with prolonged AR exposure in order to establish AR usage protocols accordingly.

ABOUT THE AUTHORS

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Cali Fidopiastis, Ph.D. *Cali M. Fidopiastis*, PhD is a Chief Scientist for Design Interactive Inc. Cali brings 20 years of experience in data modeling and visualization of complex systems to the DI knowledgebase. She is an applied neuroscientist by training who uses eXtended reality technologies to better understand the brain as it operates in the real world. Over the past 10 years, she has developed analytic and visualization techniques to assess learning and human performance within simulation-based training systems. Cali holds a Ph.D. in Modeling and Simulation from the University of Central Florida and a Masters in Sociology with focus on Experimental Psychology, as well as bachelor's degrees in biology and Psychology from the University of California, Irvine.

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INTRODUCTION

Augmented reality (AR) is rapidly being adopted by industry leaders and militaries around the globe. Most ambitious may be the United States Army's plan to rapidly field the Integrated Visual Augmentation System (IVAS; Kipman, 2021), a Microsoft HoloLens-based AR technology that will serve as "fighting and training goggles" (Suciu, 2021). IVAS will provide a "tactical edge" to realize an overmatch against current and future adversaries. IVAS can support Soldiers in visualizing and informing the battlefield (e.g., overlay intelligence data directly onto a Soldier's visual field in the IVAS headset), supporting mission rehearsal, training new skills, refreshing existing skills to maintain proficiency, and more. Within the military medical domain, the Defense Health Agency (DHA) is leading the way in deploying AR technology as a distributed learning solution, along with exploration of AR applications within primary care and operational medicine. The accelerated pace of AR adoption makes understanding and characterizing the benefits and limitations of AR-based training and operational support solutions critical, not only for optimized safety, but also for ensuring effectiveness within the AR medical training context and beyond.

Regarding safety, there is concern for potential physiological maladaptation following prolonged AR exposure. This maladaptation can take the form of postural instability, dysmetria, and degraded visual functioning, and is a result of characteristics inherent to AR Head-Worn Displays (HWDs), including visual-vestibular mismatches, restricted field of view (FOV), vergence-accommodation conflict (VAC), mismatched inter-pupillary distance (IPD), among other anomalies (Basak et al., 2019; Fang et al., 2017; Stanney, Lawson et al., 2020). There is concern that these AR HWD limitations can reduce training and operational effectiveness and impose safety concerns post exposure due to compromised functioning. For example, if training treatment of Tension Pneumothorax (TP; i.e., a condition in which air leaks into the space between the lungs and chest wall) in an AR HWD, miscalibration of 3D overlays of injuries onto a medical manikin may lead to misperception of the correct location for placing a decompression needle, which may result in costly consequences such as negative training transfer and shifts in the kinesthetic position sense when returning to the real world. Such maladaptation could compromise patient or trainee safety for activities succeeding AR HWD immersion, such as medical procedures, operating machinery, or combat engagement. Thus, while AR technology has the potential to advance operations and training, there is a need to more fully understand and characterize the physiological impacts of AR on the user.

The aims of the current exploratory study were to better quantify and qualify differences in postural stability, an indicator of cybersickness, after protracted, long duration AR exposure (2hr) across three AR display types: Microsoft (MS) HoloLens 1, Magic Leap One, and a Samsung Galaxy S5e AR Tablet. Each display type, while AR enabled, has different characteristics that may influence postural stability outcomes. For example, the MS HoloLens has a narrower field of view than the Magic Leap; however, the Magic Leap shifts visual perspectives of the end-user automatically due to its dual depth planes. Comparing the physiological impact of these different display features will make it possible to estimate display platform differences in habituation (i.e., decreased adverse response) and dual adaptation (i.e., ability of trainees to physiologically transition between virtual and real sensory environments without lingering maladaptation). If dual adaptation were to be achieved, this would constitute the genesis for a considerable breakthrough in AR training effectiveness and safety protocol development, which could catalyze widespread adoption of cost-effective, accessible AR training scenarios.

BACKGROUND

During the past few decades vast improvements have been made in both VR and AR technologies, however, many people still report experiencing physiological maladaptation, such as cybersickness, from their use (VR: Saredakis et al., 2020; Dużmańska et al., 2018; Gavgani et al., 2017; Guna et al., 2019; Rebenitsch & Owen, 2016, AR: Hughes et al., 2020; Jeon et al., 2020; Vovk et al., 2018). Cybersickness is defined as the cluster of symptoms that a user experiences during or after exposure to an immersive environment (McCauley & Sharkey, 1992), which is characterized as a physiological response (e.g., nausea, oculomotor strain, dizziness) to an unusual sensory stimulus, similar to motion sickness (Bouchard et al., 2007). Historically, it has been measured using both subjective reports (e.g., Simulator Sickness Questionnaire; Kennedy, Lane, Berbaum & Lilienthal, 1993) and objective measures (e.g., postural sway, electrodermal activity, etc.) (Stanney et al., 2020). While more than half of VR users report discomfort (Garcia-Agundez et al., 2019; Lawson, 2014), it is unclear whether AR users will experience similar maladaptation incidence and severity, as well has how AR displays may impact users' experiences.

The severity of physiological maladaptation from VR exposure has been demonstrated as proportional to exposure duration (Kennedy et al., 2000), a pattern that may possibly be mirrored for extended AR HWD usage. However, unlike VR exposure, which is oftentimes self-limiting (i.e., dropouts; Stanney, Lanham et al., 1999) due to high levels of nausea and malaise, the potentially high level of oculomotor disturbance associated with AR is not expected to lead to self-cessation, likely due to manifestation as headache and eyestrain, to which many people in our screen-based society are already accustomed. Thus, since users will likely not terminate exposure in AR despite physiological disturbances (i.e., headache and eyestrain), exposure duration could potentially be prolonged past what is comfortable in VR. This prolonged exposure could pose concern, as it remains unclear whether there will be sustained maladaptation post-AR exposure (e.g., postural instability, etc.), which could present substantial safety risks. It is thus of critical important to assess the physiological impact of AR exposure and its implications in training effectiveness, safety, and operational advantages on the battlefield.

Tactical Combat Casualty Care

Tactical Combat Casualty Care (TCCC) is a training curriculum implemented by the U.S. Army, Navy Corpsmen, Special Forces, Marines, and Air Force to train their Combat Lifesavers (CLS) on treating potentially survivable injuries that occur most often on the battlefield, including massive hemorrhage and tension pneumothorax (Bellamy, 1984; Butler, 2017; Champion et al., 2003 as cited in Kotwal et al., 2011). As DHA works through the process of updating the training curriculum for TCCC, many are considering AR as a potential solution for CLS distributed learning. Effective CLS training that transfers knowledge directly and accurately to the field is essential for decreasing preventable combat casualties. AR technology could serve a fundamental role in supporting this training need.

Training Effectiveness

Optimizing CLS training effectiveness is of particular concern for the Department of Defense (DoD) and is driving interest in AR training solutions, which could meet and exceed training needs by providing embodied (hands-on), contextualized training anytime, anywhere. Such a capability can increase access to training, both initial and recurring, thereby providing a means to increase skill retention, learning, efficiency, and reduce competency recertification requirements, potentially reducing overall training time and associated costs.

Context and embodiment are key benefits to AR training. When taken into a battlefield context, combat lifesaving is accompanied by dynamic situational factors (e.g., explosions, weapon fire, vehicle engines, etc.), taxing environmental factors (e.g., heat, cold, humidity, etc.), visual confusion (e.g., due to fog, smoke, sandstorms, etc.), and other stressors that directly impact operational performance (Merlo, 2018). Without training CLS to perform lifesaving steps surrounded by these stressful contextual variables, skills acquisition and transfer may be impeded, ultimately hindering ability to provide treatment. Similarly, embodiment (i.e., sense of self-location, sense of agency, and sense of body ownership) is highly relevant to building combat lifesaving psychomotor skills within battlefield contexts. AR supports the training of these psychomotor skills by situating the trainee within real world physical and social contexts, while allowing them to embody physical CLS activities. AR provides an anchor for visuomotor tasks and affords engagement with 'live' equipment while viewing augmented graphics and instruction, facilitating meaningful, hands-on interactions during training. The implication is that, to promote learning and transfer, AR training scenarios should incorporate contextually relevant scenarios and associated embodied behaviors that simulate appropriate physical actions and perceptions associated with critical CLS psychomotor skills. Despite the environmental benefits of training in AR, hardware-related anomalies could result in negative training transfer and risk-prone physiological maladaptation.

Training Obstacles

AR devices may result in physiological maladaptation, potentially impacting training effectiveness. As aforementioned, such maladaptation is caused by some degree of mismatch between visually displayed information and the user's senses. Perceptual mismatches and anomalies inherent to AR HWD can cause symptoms ranging from nausea and malaise to ataxia and oculomotor strain with varying incidence and severity. Prolonged VR exposure is known to lead to more severe nausea and malaise symptoms, with symptom severity proportional to the length of exposure (Kennedy et al., 2000). This type of symptomology may preclude VR users from remaining immersed for protracted amounts of time. Conversely, AR is associated with increased oculomotor discomfort (e.g., headache, eye strain), which may be more tolerable to users despite severity. If this is the case, AR users may be able to remain immersed for prolonged periods of time, which could lead to potentially severe and persistent maladaptation.

AR Displays

The oculomotor symptoms experienced in AR may stem primarily from two technology challenges: vergence-accommodation conflict (VAC) and restricted field of view (FOV). VAC occurs during AR exposure because the adaptive lens of the human eye is always focused at a fixed depth (at the display), while the viewer is being presented with and viewing a three-dimensional (3D) scene with continuous depths, which decouples the normally linked vergence and accommodation (Zhan et al., 2020). In terms of FOV, while typical human vision has a FOV of 200ºx140º, popular AR displays like the HoloLens 1 (30ºx17.5º), Magic Leap One (40ºx30º), and Samsung Galaxy S5e AR Tablet (80º horizontally) afford viewing of only a subset of the human visual field, leading to information density issues and changes in natural viewing patterns (Trepkowski et al., 2019). These discrepancies are likely what drives visual fatigue, eyestrain, vision blurring, and headache in AR displays (Fidopiastis et al., 2010), and, in turn, can negatively impact visual functioning (e.g., saccadic slowing, vestibulo-ocular reflex [VOR] destabilization) and lead to postural instability and dysmetria (Srulijes et al., 2015) that persist post-exposure (Di Girolamo et al., 2001). There is not, however, concern that narrow FOV will exacerbate cybersickness symptoms in terms of the nausea component (Fernandes et al. 2016; Rebenitsch et al, 2016). In fact, the opposite may be true; the narrow FOV and real-world referents inherent to AR may moderate the nausea and stomach upset commonly experienced in completely occluded VR systems with strong visual-vestibular discordance (Hughes et al., 2020). Specifically, as AR provides continuous viewing of real-world rest frames (e.g., walls, furniture, etc.), this may help to disambiguate virtual motion cues presented in AR HWDs with vestibular cues from real-world motion or lack thereof, which should minimize symptoms (Chang et al., 2013). Thus, even though the Samsung AR Tablet, HoloLens 1, and Magic Leap One displays have FOV significantly smaller than the human visual field, AR's instantiation of virtual elements overlaid onto reality instead of directly replacing the real-world elements, and its protective real-world rest frames, may have a reduced adverse impact on users from an overt nausea perspective (Palmisano, Allison, & Kim, 2020; Somrak, Pogacnik, & Guna, 2021), but may still pose concern with regard to physiological maladaptation.

In addition to restrictions on FOV, commonly available AR displays require varied types of user interaction. AR Tablets fall into a "hands-on" category, wherein users are required to physically hold and locomote the tablet to view the augmented environment. Conversely, AR HWDs are considered "hands-off" and allow users a full range of hand movements for interacting with their augmented environment. Extant research suggests that there are some performance differences between AR Tablets and AR HWDs. For instance, while performing the same tasks on either an AR Tablet or AR HWD, participants using the HWD completed tasks more quickly and with less physical fatigue than those using the tablet (Plasson, Cunin, Laurillau, & Nigay, 2019). However, it remains unclear how or if user interaction requirements of these displays will differentially impact cybersickness outcomes,

Objective

Utilizing AR for CLS could provide an effective outlet for contextualized, embodied battlefield ready TCCC. The current study sought to examine if different AR display types (i.e., AR HWDs vs. AR Tablets), with varying FOV and user interaction requirements (e.g., hands-off headset, hands-on tablet) impact subjective symptomatology and maladaptation. Understanding how extended immersion in various AR display types impacts physiological maladaptation will help in developing standardized protocols for AR system use that can be widely adopted within TCCC training and beyond.

METHODS

Participants

A total of 60 participants (n = 30 females, n = 30 males) participated in this study. The sample had a mean age of 27.8 (SD = 7.9), 45% were Caucasian, and 63.3% held a university degree (Associate or higher). Once AR immersion commenced, no participants dropped out of the study. Participants were recruited from February-October 2020, in the Orlando, FL area.

The study complied with the American Psychological Association Code of Ethics and was approved by Copernicus Institutional Review Board and the Human Research Protection Office (HRPO) at United States Army Medical Research and Development Command (USAMRDC). Informed consent was obtained from each participant and all participants were compensated for their time in the experiment.

Equipment

The following equipment were used in this study:

- The Samsung Galaxy S5e AR Tablet, which has a 10.5” WQXGA Super AMOLED display, a resolution of 2560 x 1600, and weighs 400g (0.88 lb).
- The MS HoloLens 1 AR HWD, which has 2.3-megapixel widescreen see-through holographic lenses (waveguides), a resolution of 1280 x 720, a holographic density >2.5K radiants, a FOV of 30º x 17.5º with a single depth plane, and weighs 579g (1.28 lb).
- The Magic Leap One AR HWD, which has widescreen see-through holographic lenses (waveguides), a resolution of 1280 x 960, a holographic density >2.5K radiants, a FOV of 40º x 30º, dual depth planes, and weighs a total of 740g (1.63 lb).
- A male Rescue Randy, which is a life-like 5’5” medical manikin with articulated joints weighing 55 lb, with weight distribution according to a human weight distribution chart.
- The Polhemus G4 wireless magnetic motion-tracking device, which was used to measure anterior-posterior postural sway. The equipment consists of a naval strap mounted sensor and transmitter connected to a Dell XPS 8930 PC. Position and orientation data from the G4 sensor were sent wirelessly to the PC while the participants were asked to maintain their balance.

Display Content

The Unity 3D Real-Time Development Platform was used to generate 2hr TCCC immersive display content. The content focused on tourniquet application and treatment of respiratory dysfunction within a TCCC battlefield context.

- Massive hemorrhage scenarios required participants to apply a tourniquet on the Rescue Randy manikin. During these scenarios, virtual massive hemorrhage AR overlays were projected onto the manikin in the form of a traumatic amputation of the right leg with pulsating bleeding and pooling blood. Instructions were also presented within the FOV of the AR HWD during the massive hemorrhage scenario.
- Respiration scenarios required participants to apply a chest seal on the Rescue Randy manikin, followed by a needle decompression of the chest after development of tension pneumothorax. During these scenarios, virtual respiration related AR overlays were projected onto the manikin in the form of a left lateral open chest wound, which over time progressed to tension pneumothorax. Instructions were also presented within the FOV of the AR HWD during the respiration scenario.
- All scenarios contained training on the DD1380 Field Medical Card (TCCC Card) and calling for a medical evacuation (MEDEVAC).

Measures

Demographics. A demographics survey was used to self-report age, sex, and education level.

Postural Stability. A postural stability measure (i.e., anterior-posterior [AP] postural sway) was used to assess maladaptation. A baseline measure was taken pre-exposure and then additional measures were taken immediately after and at 15 min increments for 1hr post exposure. Three-dimensional measurements of postural sway, as measured via the Tandem Rhomberg Test (Johnson et al., 2005), were collected using the Polhemus G4. During the test, participants were asked to remove their shoes, stand with their non-dominant foot directly in front of their dominant foot, center their weight equally across both feet, fold their arms at shoulder level, close their eyes, and hold steady for 60 sec. Two trials of 60 sec were collected. For each trial, position and orientation data from the G4 sensor were sent wirelessly to the Dell PC, while the participant was asked to maintain their balance. Change in AP sway from baseline to post exposure measurement was the maladaptation metric. Possible sources of electromagnetic interference and position inaccuracy were controlled for.

Simulator Sickness Questionnaire. Subjective cybersickness symptoms were assessed via the SSQ (Kennedy et al., 1993), including the SSQ Total Score (TS) and Oculomotor (O) subscale. This questionnaire assesses symptoms on a scale of 0 (none) to 3 (severe) and then sub-divides the symptoms into three symptomatic subcategories: Nausea (N), Oculomotor (O), and Disorientation (D). The Total Score is compiled based on weighted totals of the three subscales.

Stereo Butterfly SO-005 Test. Evaluates random dot stereo depth perception for both gross stereopsis (2500 to 1200 seconds of arc) and fine depth perception (Stereo Optical Company Inc., 2009).

Procedure

The experiment involved the following phases: pre-screening, on-site screening, pre-testing, immersive exposure, and post-testing.

During pre-screening, any participants reporting any exclusion criteria (neurological impairments, musculoskeletal problems of the knee, ankle, shoulder, and/or elbow, loss in depth perception, <20/20 corrected visual acuity, inner-ear anomalies, history of seizures, or implanted conductive or electronic devices) were informed they did not qualify for participation. Participants who met pre-screening eligibility proceeded to on-site screening. During the on-site screening phase, participants provided written informed consent and filled out the SSQ; those with TS scores above 12 were excluded from the study, as this was an indication of ill health. The Stereo Butterfly Test was also administered and those without stereoscopic vision or other noted visual anomalies other than myopia/hyperopia were excluded from the study. Assessment of alcohol and medication consumption was also taken; participants who were under the influence of alcohol or drugs were excluded from the study. During the pre-testing phase, participants completed the demographics questionnaire and baseline measure of anterior-posterior postural sway.

During the immersive exposure phase, participants were randomized to a Display Type (AR Tablet, MS HoloLens 1, Magic Leap One) and fitted with the assigned display. Participants were then exposed to the 2hr TCCC training content. During exposure, AR content was overlaid on the Rescue Randy manikin by virtual placement of the content. Each AR device scanned the experimental space and participants placed a virtual casualty over top of the Rescue Randy. The system allowed for initial placement and then fine adjustment within 3 degrees of freedom (up/down, front/back, and left/right). Placement of the virtual casualty was confirmed by the experimenter before each participant began the TCCC scenarios. Participants then completed as many massive hemorrhage and respiration scenarios as they could get through in the 2hr exposure time.

During the post-testing phase, AP sway and SSQ were assessed immediately after (AE [aftereffects] 1), and in 15 min increments for a total of 60 min (AE2-AE5) post exposure. Participants were then debriefed, thanked, and paid for participation.

Analysis Approach

First, frequency analyses were completed on the demographic survey items. Second, observational frequencies were completed to determine how much of the sample experienced increases in anterior-posterior postural sway following AR immersion. Third, analyses of variance (ANOVA) were completed to assess display type differences in amount of anterior-posterior postural sway change from baseline.

RESULTS

Participants were able to sustain long duration AR exposure, as there were no dropouts and no emetic responses. Further, the SSQ TS results (see Table 1) were relatively high immediately post exposure for all AR display types (AE1: HoloLens 1 Mean SSQ TS= 20.57, SD=17.81; Magic Leap One Mean SSQ TS=19.82, SD=16.46; AR Tablet

Mean SSQ=16.27, SD=17.72) and then dissipated to low levels by AE5 in the HoloLens 1 (Mean SSQ TS=6.73, SD=11.36) but persisted across all post exposure measurement periods in the Magic Leap One (AE5 Mean SSQ TS=14.59, SD=14.35) and AR Tablet (AE5 Mean SSQ TS=17.02, SD=21.21). A similar pattern was seen in the SSQ oculomotor subscale. SSQ O results were high immediately post exposure for all AR display types (AE1: HoloLens 1 Mean SSQ O= 21.22, SD=16.61; Magic Leap One Mean SSQ TS=23.12, SD=17.47; AR Tablet Mean SSQ=16.3, SD=17.44) and then dissipated to low levels by AE5 in the HoloLens 1 (Mean SSQ TS=8.34, SD=13.89) but persisted across all post exposure measurement periods in the Magic Leap One (AE5 Mean SSQ TS=18.57, SD=17.47) and AR Tablet (AE5 Mean SSQ TS=18.95, SD=19.75). These results suggest that the HoloLens 1 may be less of a physiological burden than the other AR display types. It further suggests that the multiple depth planes in the Magic Leap One may not be providing a benefit with regard to physiological impact. From a subjective perspective, the SSQ results indicate that the oculomotor system, in particular, was affected by AR exposure.

Table 1. SSQ Total Scores and Oculomotor Subscale at AE1 and AE5

AR Display Type	AE1-SSQ TS Mean (SD)	AE5-SSQ TS Mean (SD)	AE1-SSQ O Mean (SD)	AE5-SSQ O Mean (SD)
AR Tablet	16.27 (17.72)	17.02 (21.21)	16.30 (17.44)	18.95 (19.75)
HoloLens 1	20.57 (17.81)	6.73 (11.36)	21.22 (16.61)	8.34 (13.89)
Magic Leap One	19.82 (16.46)	14.59 (14.35)	23.12 (17.47)	18.57 (17.47)

Next, we explored if prolonged AR exposure was associated with maladaptation in posture. Postural control is dependent on visual, as well as other sensory inputs including vestibular, proprioceptors, and mechanoreceptors (Diener & Dichgans, 1988). If these inputs are affected by AR exposure, based on altered information from sensory receptors due to VAC, reduced FOV, etc., postural instability can result. The results indicate that shifts were seen in AP sway after 2hr AR exposure. Immediately following immersion, HoloLens 1 participants had an average 352% increase in their AP sway from baseline compared to a 19% increase in Magic Leap One participants and a 12% decrease in AR Tablet participants (Table 2, Figure 1). During the 15 to 45 min post-exposure measurements, under all AR display conditions participants experienced similar plateaued levels of AP sway change from baseline, with HoloLens participants experiencing a noticeable uptick at 1hr post-exposure (see AE5 in Table 2). The HoloLens 1 had, on average across all post exposure measurements, 99.4% more AP sway as compared to the Magic Leap One and 120.4% more AP sway as compared to the AR Tablet; these differences approached significance ($F(2,59) = 2.90$, $p = 0.06$). The increase in AP sway associated with the HoloLens 1 was profound and as, or potentially more, severe than is typically seen with alcohol intoxication, which is known to adversely affect human performance, including adverse effects on attention, judgment, reasoning, and decision making (Brumback, Cao, & King, 2007; Modig, Fransson, Magnusson, & Patel, 2012). Thus, there is concern that the postural sway associated with protracted, long duration AR exposure could have significant implications to human performance, both during and for prolonged periods post exposure.

Table 2. Anterior-Posterior Sway Average % Change (*SD*) from Baseline After Extended Exposure

	Average Percent Change in Sway from Baseline (*SD*)				
Display Type	**AE1**	**AE2**	**AE3**	**AE4**	**AE5**
AR Tablet	-0.12 (0.30)	-0.11 (0.42)	-0.06 (0.39)	-0.05 (0.52)	-0.13 (0.55)
HoloLens 1	3.52 (9.33)	0.02 (0.30)	0.21 (0.77)	0.14 (0.69)	1.66 (4.58)
Magic Leap One	0.19 (0.62)	0.18 (0.58)	0.11 (0.63)	0.04 (0.59)	0.06 (0.42)

Note. AE = after effects time points.

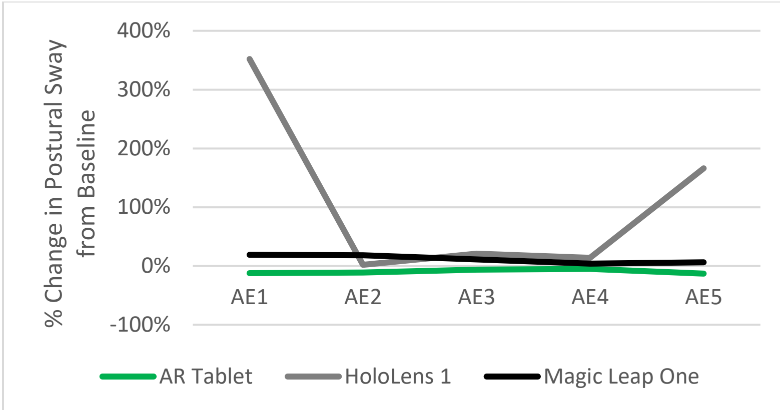

Figure 1. Anterior-Posterior Postural Sway Average % Change (*SD*) from Baseline After Extended Exposure

DISCUSSION

CLS training for battlefield ready TCCC in AR may provide an efficacious platform for contextualized, embodied military medical learning. Based on the results from this study, prolonged AR training exposure may be a sustainable CLS alternative. There were zero dropouts after 2hr of AR exposure, indicating habituation after long periods, contrasting VR exposure where symptoms become increasingly exacerbated across exposure time and dropouts are prevalent. It may be that prolonged AR exposure better allows the eyes to adjust to the visual condition in AR HWDs, resulting in less severe subjective symptomology. Yet, observable post-AR exposure physiological maladaptation was found in this study, with AP sway increases seen, particularly with the HoloLens 1. HoloLens participants had, on average, 352% increase in AP sway from baseline, while Magic Leap One demonstrated a very slight increase in and AR Tablet a small decrease in AP sway. Based on these results, it may be beneficial to implement a dual-technology training protocol, where AR Tablets, which do not have demonstrable post-exposure postural sway, are used to deliver longer duration declarative knowledge scenarios and AR HWDs are reserved for fully contextualized, embodied training experiences that focus on hands-on procedural and conditional (strategic) knowledge that is linked to context.

Taken together, the results suggest that prolonged AR exposure resulted in habituation (participants felt fine) but not dual adaptation, as high levels of AP sway were seen post exposure. Additionally, post exposure AP sway was impacted by AR display type, with the HoloLens 1 resulting in profoundly more sway as compared to the Magic Leap One and AR Tablet. The high level of postural sway associated with the HoloLens 1 poses concern with regard to safety and functioning post exposure. Moving forward, it will be important to quantify the adverse physiological effects associated with prolonged AR exposure using larger sample sizes, diverse exposure protocols, and additional objective measures in order to establish AR usage protocols accordingly.

Tentative Usage Protocols and Expectations

- Prolonged AR use (2hr) appears to be well-tolerated, with signs of habituation indicated by rapid recovery post exposure from subjective symptomatology, particularly in the HoloLens 1.
- Prolonged AR use (2hr) does not appear to lead to dual adaptation (i.e., ability of trainees to physiologically transition between virtual and real sensory environments without any lingering maladaptation), which presents human performance and safety concerns.
- Due to maladaptation:
    - It is recommended that postural stability be monitored during and after AR exposure to ensure safety.
    - To facilitate dual adaptation, consider use of:
        - Protracted, long duration (4+hr) AR exposure and combine with daily repetition until no adverse aftereffects are detected.
        - Intermittent, short duration exposure (30 min) with short breaks (5 min).
- Expect oculomotor disturbances with AR exposure and mitigate by:
    - Using well calibrated display settings that ensure projected images are not too blurry, bright, etc.

  - Avoiding sustained near-point tasks; methodically employ a combination of close vs. far work to reduce the impact of VAC.
- Consider implementing dual-technology AR training protocols:
  - Use AR Tablets to deliver longer duration declarative knowledge scenarios.
    - AR Tablets could be used to supplement classroom with contextualized training for improving retention of basic terminology, facts, concepts, and procedures.
  - Reserve AR HWDs for fully contextualized, embodied training experiences, focusing on hands-on procedural and conditional (strategic) knowledge that is linked to context.
- Continue development of adaptive AR systems to personalize training experiences based on trainee proficiency and physiological well-being, with indications of increased postural sway triggering cessation of AR exposure, as with zero drops in the current study, self-cessation is not anticipated.

CONCLUSION

The results suggest a selective reduction in cybersickness sensitivity, as assessed via subjective report (SSQ), over protracted (2hr) AR exposure. At the same time, increases in post-exposure AP sway suggest long duration AR exposure can be expected to be associated with physiological maladaptation. It is important to note that these effects may be different depending on the type of AR display used, with the HoloLens 1 potentially being most subjectively tolerable but most likely to lead to maladaptation. It is also interesting to note that AR behaved quite differently than VR regarding physiological impact. Past research has shown that subjectively reported cybersickness symptoms associated with long duration VR exposure are profound and regularly lead to dropouts and a reliable emetic response rate. The current study demonstrated that protracted, long duration AR exposure was associated with low to moderate levels of subjectively reported cybersickness, no dropouts, and no emetic responses. Thus, long duration AR exposure may be more tolerable than VR exposure, which may lead to protracted AR use and concern for associated maladaptation (i.e., postural sway, saccadic slowing, VOR shifts, dysmetria) that could compromise human functioning and pose safety concerns post exposure. It is highly recommended that future studies explore the potential of longer (4+hr) exposure durations with repetition (2- 4 sessions) to determine if dual adaptation (seamless transition between AR and real-world) can be achieved, which will enhance AR safety, thereby increasing suitability of AR for training and operational support. In general, there is a need for further research to identify how to foster dual adaptation in AR systems to ensure this technology is safe and effective to use for military medical training and beyond.

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Non-Endorsement Disclaimer:

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