Monitoring with Head-Mounted Displays: Performance and Safety in a Full-Scale Simulator and Part-Task Trainer

David Liu, BE (Hons)*

Simon A. Jenkins, BMBS, FANZCA†‡

Penelope M. Sanderson, PhD, FASSA*§‖

Marcus O. Watson, PhD‖

Terrence Leane, RN, GDPH, GDNursSci¶

Amanda Kruys, MBBS†

W. John Russell, MBBS, DPhil, DIC, FANZCA, FRCA†

BACKGROUND: Head-mounted displays (HMDs) can help anesthesiologists with intraoperative monitoring by keeping patients' vital signs within view at all times, even while the anesthesiologist is busy performing procedures or unable to see the monitor. The anesthesia literature suggests that there are advantages of HMD use, but research into head-up displays in the cockpit suggests that HMDs may exacerbate inattentional blindness (a tendency for users to miss unexpected but salient events in the field of view) and may introduce perceptual issues relating to focal depth. We investigated these issues in two simulator-based experiments.

METHODS: Experiment 1 investigated whether wearing a HMD would affect how quickly anesthesiologists detect events, and whether the focus setting of the HMD (near or far) makes any difference. Twelve anesthesiologists provided anesthesia in three naturalistic scenarios within a simulated operating theater environment. There were 24 different events that occurred either on the patient monitor or in the operating room. Experiment 2 investigated whether anesthesiologists physically constrained by performing a procedure would detect patient-related events faster with a HMD than without. Twelve anesthesiologists performed a complex simulated clinical task on a part-task endoscopic dexterity trainer while monitoring the simulated patient's vital signs. All participants experienced four different events within each of two scenarios.

RESULTS: Experiment 1 showed that neither wearing the HMD nor adjusting the focus setting reduced participants' ability to detect events (the number of events detected and time to detect events). In general, participants spent more time looking toward the patient and less time toward the anesthesia machine when they wore the HMD than when they used standard monitoring alone. Participants reported that they preferred the near focus setting. Experiment 2 showed that participants detected two of four events faster with the HMD, but one event more slowly with the HMD. Participants turned to look toward the anesthesia machine significantly less often when using the HMD. When using the HMD, participants reported that they were less busy, monitoring was easier, and they believed they were faster at detecting abnormal changes.

CONCLUSIONS: The HMD helped anesthesiologists detect events when physically constrained, but not when physically unconstrained. Although there was no conclusive evidence of worsened inattentional blindness, found in aviation, the perceptual properties of the HMD display appear to influence whether events are detected. Anesthesiologists wearing HMDs should self-adjust the focus to minimize eyestrain and should be aware that some changes may not attract their attention. Future areas of research include developing principles for the design of HMDs, evaluating other types of HMDs, and evaluating the HMD in clinical contexts.

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Head-mounted displays (HMDs) have been proposed as a way for anesthesiologists to monitor their patients' vital signs while performing procedures that prevent them from looking toward the patient monitor.[1,2] The head-up displays (HUDs) used in aviation are similar to HMDs, allowing pilots to monitor their instruments and the immediate airspace simultaneously,[3] but HUDs are mounted on the windshield. Although there seem to be performance advantages with HMDs in anesthesia and other domains, aviation studies have

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From the *School of Information Technology and Electrical Engineering, The University of Queensland, Brisbane; †Department of Anaesthesia, Pain Medicine and Hyperbaric Medicine, Royal Adelaide Hospital; ‡Centre for Sleep Research, University of South Australia, Adelaide; §School of Psychology, The University of Queensland; ‖School of Medicine, The University of Queensland, Brisbane; and ¶Nursing and Patient Care Services, Royal Adelaide Hospital, Adelaide, Australia.

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Address correspondence to David Liu, BE (Hons), Department of Anesthesiology, University of Utah, 3C444 SOM, 30 North 1900 East, Salt Lake City, UT 84132-2304. Address e-mail to naskies@acm.org.

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indicated potentially serious safety concerns with HUDs that have not been investigated for HMDs in anesthesia.[2]

HMDs offer many potential benefits for anesthesia patient monitoring. In two initial clinical evaluations,[4,5] anesthesiologists reported that HMDs would be useful in operating rooms (ORs). They described the benefits of HMD as being uninterrupted patient monitoring,[4,5] less need to move to see the monitor,[4,5] and the ability to see vital signs during laryngoscopy.[5] Full-scale simulator studies have found that anesthesiologists can detect critical patient events faster while wearing a HMD than while using standard monitoring alone[6] and that they spend more time attending to the patient than to the monitor.[7] A study of highly distracted anesthesiologists who used advanced displays to monitor patients found that the anesthesiologists rated monitoring as being easier with the HMD than with a control condition.[8] They also believed (mistakenly) that they detected events faster with the HMD.

There are several limitations of the research methods used to evaluate HMDs in the three reported full-scale simulator studies,[6–8] which means that the findings may not generalize to normal anesthesia practice. First, participants in two of the studies were physically constrained either by being tethered to the patient monitor with a connecting cable,[6] or by being required to remain seated while performing a distractor task.[8] Second, the scenarios used in another two of these studies[6,7] displayed the simulated patient's vital signs but the scenarios did not reproduce the anesthesiologists' interactions with other staff, distractions, and other nonmonitoring but relevant cues in the OR.[9,10] Finally, the events presented to participants in the three reported studies consisted only of changes to the simulated patient's vital signs and did not include events occurring in the patient vicinity or in other locations within the OR.

Despite the methodological limitations of the earlier studies, the benefits reported for HMDs in anesthesia monitoring are similar to the benefits reported for HUDs in the aviation literature. However, the aviation literature also reveals a range of cognitive and perceptual issues with HUDs that may have adverse effects on safety,[11] but that have not been investigated with HMDs in the context of anesthesia.[2]

Two issues in particular may be cause for concern. First, although HUDs can improve users' ability to detect events in the displays of sensed data, there is also a tendency for users to miss salient, unexpected events in the outside world:[2] the so-called inattentional blindness phenomenon. In flight simulator studies, pilots on approach to land are more likely to miss a runway incursion when using a HUD than when using a head-down display, despite the runway incursion being clearly within their field of view.[11] This phenomenon has been replicated with HMDs in laboratory studies.[12]

Second, cognitive and perceptual problems may occur when the HMD is focused at a different optical distance from an object that the wearer is looking at in the outside world.[13] Misaccommodation occurs when the focus of the HMD wearer's eyes lapse toward their resting point of accommodation and away from the display's focus plane.[11] Misaccommodation can decrease visual acuity and lead to worse target detection. Users in environments in which there are frequent disparities in optical distance between the HMD and the outside world are more likely to be affected by inattentional blindness.[13] Furthermore, there is no consensus in the literature on the optical distance at which HMDs should be focused to mitigate misaccommodation.[13]

If the above cognitive and perceptual problems were to occur with HMDs used for patient monitoring, then patient safety could be compromised. Anesthesiologists monitoring with a HMD may believe that they are vigilantly monitoring their patient, but may not realize that they have missed a safety-critical event occurring in the surrounding OR.

In this article, we report the results of two experiments that investigated whether using a HMD would render anesthesiologists more or less likely to detect unexpected but safety-critical events under two types of conditions: 1) when the anesthesiologist is monitoring a simulated patient during a surgical procedure and 2) when the anesthesiologist is monitoring the simulated patient while also performing a procedure.

METHODS

Experiment 1—Inattentional Blindness

The aim of this experiment was to test the HMD in a full-scale simulator using scenarios that are more representative of clinical practice and where the anesthesiologist is less physically constrained than in earlier studies to determine 1) whether HMDs worsen inattentional blindness in anesthesia, as they can in other domains and 2) whether the focal depth of the HMD affects anesthesiologists' event detection performance.

Design

A 3 × 2 × 4 repeated-measures experimental design was used with one independent variable, Display, and two controlled variables, Distractor Task Location and Event Location. Display referred to the patient monitors available to participants; that is, whether the HMD was available in the scenario and, if so, whether the focal depth of the HMD was set near or far (Control, HMD-Near, and HMD-Far). The Event Location and Distractor Task Location variables were controls for, respectively, where unexpected events were presented in the OR, and where participants' attention would be drawn at the onset of those events. Event Location indicated that the event was apparent 1) on the visual monitor or anesthesia machine but not the HMD (Monitor only), 2) on the HMD and the visual monitor (HMD + Monitor), 3) on or around the patient (Patient), or 4) elsewhere in the OR. Distractor Task Location was either Near or Far.

If HMDs are useful for monitoring, then when anesthesiologists use a HMD, they may spend a smaller percentage of their time looking at the standard patient monitor than when they do not use a HMD. Furthermore, if anesthesiologists can detect critical patient events faster when using a HMD, as reported in the literature, then they may detect events relatively faster in the HMD + Monitor location only, when the events appear on the HMD display. Moreover, if the inattentional blindness phenomenon is worsened by HMDs, then when they use a HMD, anesthesiologists may detect the Monitor only, Patient, and OR events in the far domain more slowly.

If misaccommodation and focal depth affect the use of HMDs in anesthesia, then we would expect differences in anesthesiologists' ability to detect events in the HMD-Near versus HMD-Far display conditions. Furthermore, if one focal depth provides significantly better visual acuity or comfort for the anesthesiologists than another focal depth, then we would expect anesthesiologists to spend proportionately less time looking toward the standard monitor with that focal depth (representing a greater reliance on the HMD).

Participants

This study received Human Research and Ethics Committee approvals from the Royal Adelaide Hospital and The University of Queensland. Twelve anesthesiologists from the Royal Adelaide Hospital (seven residents and five attendings) with normal or corrected-to-normal 20/20 binocular vision (or better) participated in the study.

Apparatus

Participants provided anesthesia to a METI ECS™ (Sarasota, FL) mannequin in a simulated OR environment at the Royal Adelaide Hospital. We extended the ECS™ using custom software to provide high fidelity capnography,[14] inhaled gas monitoring, and automatic cycling of noninvasive arterial blood pressure.[15] There was a team of five actors in the simulator with the participant: a qualified anesthetic assistant, and actors as surgeon, surgical nurse, medical student, and circulating nurse. Two controllers coordinated the actors using ear-piece radios from an adjoining control room.

Participants wore a Microvision Nomad™ ND2000 HMD (Bothell, WA) connected to a belt-worn battery pack and driven by a Sony Vaio™ U50 computer. The Nomad HMD is a scanning retinal display that uses a laser to project a monochrome red image onto a single transparent monocle that reflects the image directly on the wearer's retina. The HMD was set to a focal depth of 50 cm (2 diopters) in the HMD-Near condition and optical infinity (0 diopters) in the HMD-Far condition. Participants were not tethered to the anesthesia machine and thus were free to move around the OR. In the Control condition, the monocle was removed from the HMD visor but participants still wore the rest of the HMD equipment.

Figure 1. An anesthesiologist intubates a mannequin while monitoring with a head-mounted display (HMD) in Experiment 1. The HMD projects a subset of the vital signs presented on the patient monitor into the anesthesiologist's field of view (Fig. 2). The simulated patient monitor (in the background) includes waveforms (electrocardiogram, Spo_2, and CO_2) and numerical vital signs (heart rate, Spo_2, ETCO_2, noninvasive arterial blood pressure (NIBP), temperature, and end-tidal/inspired: agent, N_2O and O_2).

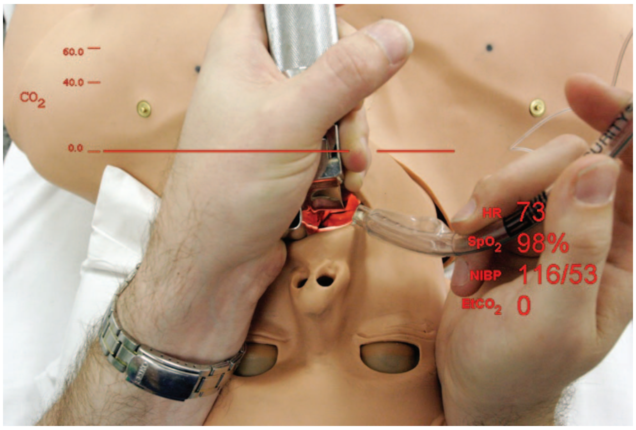

Figure 2. A simulated image showing what participants in Experiment 1 would have seen while intubating the mannequin with the head-mounted display (HMD). The HMD displayed a CO_2 wave form and numerical heart rate, Spo_2, ETCO_2, and noninvasive arterial blood pressure. Note that the CO_2 trace and end-tidal value are temporarily absent during intubation.

In all monitoring conditions, the standard patient monitor was a video graphics array screen mounted within the anesthesia machine. The monitor displayed the simulated patient's vital signs (Fig. 1) with audible pulse oximetry tones but auditory alarms disabled. The HMD displayed a subset of information available on the standard monitor (Fig. 2).

Participants also wore a wireless head-mounted video camera and lapel microphone in all conditions. Additional video cameras captured opposite ends of the OR and the patient monitor. The four video sources were combined with audio from the control room into a quad format video feed.

Table 1. Overview of the Unexpected Events Presented to Participants in Experiment 1

Event	Event description	Distractor task description	Event location	Distractor task location
Training scenario—laparotomy, possible hemicolectomy				
1	Suction disconnected	Surgeon comments on procedure	Monitor only	Far
2	Cricoid pressure removed prematurely	Intubation	Patient	Near
3	Marked bradycardia (HR <40)	Medical student asks question from doorway	HMD + Monitor	Far
4	Removal of soft toy from surgical wound	Charting	OR	Near
Scenario 1—left fem-pop bypass				
1	Patient's arm falls from support	Intubation	Patient	Near
2	ECG disconnection (HR remains visible due to oximeter)	Discussion with surgeon	Monitor only	Far
3	Surgeon preps incorrect side	Discussion of lunch orders with nurse at doorway	Patient	Far
4	Light anesthesia (tachycardia, hypertension)	Charting	HMD + Monitor	Near
5	Temperature display incorrect	Checks medication label for surgical nurse	Monitor only	Near
6	Patient bleeding (surgical suction bottles rapidly fill, blood-soaked packs visible)	Question for anesthesiologist from doorway	OR	Far
7	Incorrect patient name on form	Signing transfusion request form	OR	Near
8	Life-threatening arrhythmia (ventricular tachycardia, HR 180)	Receiving a phone message relayed across OR	HMD + Monitor	Far
Scenario 2—anterior resection				
1	Surgeon leaves operating room	Drawing up induction drugs	OR	Near
2	Patient opens eyes	Intubation	Patient	Near
3	Breathing circuit leak (audible leak, bellows fails to fill, no CO_2 change)	Discussion with medical student	Monitor only	Near
4	Bronchospasm (CO_2 waveform change, $ETco_2$ decreases)	Nurse asks question from across OR	HMD + Monitor	Far
5	Volatile too high (visible on agent analysis and vaporizer)	Medical student asks question	Monitor only	Far
6	IV line disconnection	Nurse attracts attention from across the OR	Patient	Far
7	Minor arrhythmia (atrial fibrillation, no significant HR or BP change)	Item (book) handed to participant	HMD + Monitor	Near
8	Medical student faints	Receiving a phone message relayed across OR	OR	Far
Scenario 3—left knee replacement (no tourniquet used)				
1	Surgical delay from missing equipment	Drawing up drugs	OR	Near
2	Nurse leaves laryngoscope on patient	Discussion with surgeon	Patient	Far
3	ST segment depression	Charting	Monitor only	Near
4	Hypovolemia	Phone message relayed through circ nurse	HMD + Monitor	Far
5	IV drip occlusion	Signing transfusion request form	Patient	Near
6	Volatile agent empty (visible on agent analyzer)	Discussion with nurse across OR	Monitor only	Far
7	Circuit disconnection	Drawing up medication	HMD + Monitor	Near
8	Anesthetic nurse administers blood without appropriate checking routine[a]	Discussion with surgeon	OR	Far

The three test scenarios each contained eight events representing all combinations of the Distractor Task Location and Event Location variables. Events were paired with a distractor task to provide a consistent control for the anesthesiologist's attention at the event onset.

[a] Data from this event have been reported in a separate analysis of interruptions and prospective memory.[16,17]

Scenarios

Three 35–40-min test scenarios and one 20-min training scenario were developed for the experiment, in which participants provided anesthesia to a simulated patient undergoing surgery. Although tightly scripted for the actors, scenarios were designed to be familiar to the participants, requiring participants to complete typical OR tasks at their discretion and including a range of clinical distractions.

There were eight different events embedded in each test scenario, corresponding to the eight permutations of the four Event Location and two Distractor Task Location controlled variables (Table 1).[16,17] The timing of Events and Distractor Tasks was managed by coordinators in the simulator control room so that the Distractor Task occurred in the intended near or far location at exactly the same time that the Event occurred. Participants experienced each test scenario under a different display condition, which was counterbalanced using a Latin Squares design (Table 2).

Procedure

The experiment ran for about 4–5 h and had four phases: consent and orientation, training, scenarios, and final questionnaires. During the orientation phase, participants completed a background questionnaire and confirmed their ability to read text at the near and far focal depths by reading a Snellen chart at 6 m, followed by a smaller Snellen chart at 0.5 m.

During the training phase, participants learned to use the HMD, and they read the numbers displayed on the HMD to the experimenter for both focal depths. After a brief orientation to the simulator, participants performed the training scenario and then completed a posttrial questionnaire in a different room.

During the scenario phase, the process of participating in a scenario and completing a posttrial questionnaire was repeated for the three test scenarios.

Table 2. Counterbalancing of Participant Expertise and the Presentation Order of Display Conditions in Experiment 1

Participant	Expertise	First scenario	Second scenario	Third scenario
1	Attending	HMD-Near	Control	HMD-Far
2	Attending	HMD-Far	HMD-Near	Control
3	Resident	Control	HMD-Near	HMD-Far
4	Attending	HMD-Far	Control	HMD-Near
5	Attending	HMD-Near	HMD-Far	Control
6	Attending	Control	HMD-Far	HMD-Near
7	Resident	HMD-Near	Control	HMD-Far
8	Resident	HMD-Far	HMD-Near	Control
9	Resident	Control	HMD-Near	HMD-Far
10	Resident	HMD-Far	Control	HMD-Near
11	Resident	HMD-Near	HMD-Far	Control
12	Resident	Control	HMD-Far	HMD-Near

During scenarios, classical music was played in the simulator at a low volume to provide ambient sound.

Finally, participants completed a postexperiment questionnaire and further inventories.

Analysis

Video data were captured in a quad video display format. The video data were analyzed to determine the onset time of an event (when event symptoms are first visible in the video) and the time of detection (when the participant makes a comment about the event or begins a corrective action) for the 24 events presented to each participant. Differences in the number of events detected and event detection times across trials were tested for significance with Statistica^{TM} 8 (StatSoft, Tulsa, OK) using repeated-measures analysis of variances (ANOVAs) followed by Tukey Honestly Significant Difference (HSD) tests with $\alpha = 0.05$. Events not detected were assigned nominal detection times of 180 s.

Changes in where participants were looking ("gaze location") during scenarios were coded by a trained coder using a custom-designed video analysis tool. Gaze location was coded using three categories: Anesthesia machine, Patient, and Other. Objective rules were established for distinguishing the three categories and for identifying precisely the start and end time of gaze toward a specific location. From these data, several dependent measures were derived: frequency of gazes toward a gaze location and total time spent looking at a gaze location.

The scenarios were also divided into five phases of anesthesia: Preparation, Induction, Intubation, Draping, and Surgery. Events defining transitions between phases were as follows:

- Preparation to Induction: the first drug administered
- Induction to Intubation: participant picks up the laryngoscope
- Intubation to Draping: participant tells the surgeon to begin
- Draping to Surgery: the surgeon says "starting now" (or equivalent).

The following dependent measures were tested for significant differences among conditions using repeated-measures ANOVAs followed by Tukey HSD tests: 1) mean number of events detected, 2) mean event detection times, 3) the percentage of time the participants spent looking at a specific location during the five phases of anesthesia in each scenario, and 4) the frequency with which participants gazed toward specific locations.

Experiment 2—Constrained Context

The aim of Experiment 2 was to determine whether HMDs would be useful for anesthesiologists when they are operationally constrained by a simulated fiberoptic intubation task and physically constrained while operating the scope with both hands and watching the scope's video output.

Design

A 2 × 4 repeated-measures experimental design was used with one independent variable, Display (Control versus HMD conditions), and one controlled variable, Event. All participants, therefore, experienced both the Control and HMD conditions of the Display variable, and all four Events (Table 3) within each Display condition. The dependent variable was the time to detect a series of unexpected vital sign changes on the patient monitor or on the HMD.

If the anesthesiologist's means for maintaining vigilance is compromised under constrained conditions, then the anesthesiologist will detect patient events faster in the HMD condition than in the Control condition. Because participants are required simply to detect patient events, rather than to judge clinical significance, we expected the HMD to show an advantage across all events.

Participants

This study received Human Research and Ethics Committee approvals from the Royal Adelaide Hospital and The University of Queensland. Twelve anesthesiologists from the Royal Adelaide Hospital (six residents and six attendings) participated voluntarily after providing their written consent.

Apparatus

Participants performed a navigation task on a Dexter® Endoscopic Dexterity Trainer (Replicant Medical

Table 3. Synopsis of the Four Unexpected Events Presented to Participants in Experiment 2

Event (clinical correlate)	ECG	CO_2	$ETco_2$	NIBP	HR
Baseline	Sinus rhythm	RR = 12	30 mm Hg	116/54	76 bpm
Event 1 (ischemia)	Ectopic beat + ST depression at onset of event	—	—	—	Increases after 120 s
Event 2 (excess sedation)	—	Respiratory rate halves over 120 s	—	—	Increases after 120 s
Event 3 (light anesthesia)	—	Respiratory rate doubles	Decreases for one breath	Increases to 182/103 at onset of event	Increases after 120 s
Event 4 (hypovolemia)	—	—	—	Decreases to 84/41 at onset of event	Increases after 120 s

The two scenarios contained the same four events but the events were presented in different orders. The electrocardiogram was displayed on the standard monitor only, whereas the remaining parameters were displayed on both the standard monitor and the head-mounted display (HMD).

Figure 3. An Experiment 2 participant (center) operating the fiberoptic scope with both hands and watching the scope's monitor. A simulated patient's vital signs were displayed on a monitor located directly behind the participant (right), and also on the head-mounted display (HMD) depending upon the display condition. The experimenter (center-right) sat in the corner of the room and answered the participant's questions.

Simulator Ltd, Wellington, New Zealand). They were physically constrained by operating a fiberoptic scope with both hands while watching an image on the scope's monitor that was located in front of their "patient" (Fig. 3).

While navigating the maze, participants simultaneously monitored the simulated patient's vital signs that were displayed on a monitor located directly behind them (and on the HMD when applicable) for abnormal changes. The vital signs were generated using a METI ECS™ with custom extensions.[14,15] Participants were free to turn back to look at the patient monitor whenever they wished. This monitor and simulator configuration was similar to Experiment 1, except that the METI ECS™ software was disconnected from the physical mannequin in Experiment 2. In the HMD conditions, the HMD focus was self-adjusted by participants for subjective maximum clarity while they were looking at the scope monitor.

Scenarios

Each participant experienced two 6–10-min scenarios during which they performed the navigation task and monitored the simulated patient. The experimenter was present in the room and answered questions about the task. Each scenario contained four independent events intended to simulate ischemia, excess sedation, light anesthesia, and hypovolemia (Table 3). The events were identical in both scenarios but were presented in a different order. All participants experienced the two scenarios in the same order, but the order of display conditions was reversed for alternate participants.

Procedure

Participants completed a background questionnaire after providing consent, followed by a brief training scenario to familiarize themselves with operating the fiberoptic scope, monitoring with the HMD, detecting events, and completing questionnaires. For the experimental scenarios, participants were asked to assume that they were doing a fiberoptic intubation by themselves in the OR so they would have to monitor the "patient" accordingly, but no tradeoffs between the navigation task and the patient monitoring task were suggested. The participants then performed the two scenarios and completed a postsession questionnaire after each scenario. Finally, participants completed a postexperiment questionnaire and were then debriefed.

Analysis

Video data were captured in a quad display format as in Experiment 1. Participants' event detections and location of gaze were coded in the same way as in Experiment 1, with the Anesthesia machine and Patient codes directly comparable with Experiment 1, and the Other code comprising only three instances. Event detection times between the two Display conditions were tested for significance with Statistica™ using repeated-measures ANOVAs with $\alpha = 0.05$ and planned comparisons between the Display conditions for each Event. Differences in participants' gaze location and questionnaire responses for the two Display conditions were also tested for significance using repeated-measures ANOVAs.

Table 4. The Performance (Number of Events Detected, and Event Detection Times) and Behavioral Results (Monitor Scanning Patterns) for the Three Display Conditions in Experiment 1

Measure	Control	HMD-Near	HMD-Far
Mean number of events detected (of 8)	6.1 (0.3)	5.8 (0.3)	6.2 (0.4)
Mean event detection times (s)	72.8 (18.4)	77.6 (18.2)	78.3 (18.5)
Near distractor tasks only (s)			
HMD + Monitor	11.4 (2.1)	15.3 (3.9)	13.0 (2.3)
Monitor only	63.7 (17.6)	85.2 (23.6)	76.4 (17.9)
Patient	95.4 (25.0)	88.5 (21.7)	78.5 (22.6)
Operating room	149.4 (16.9)	152.8 (16.0)	152.5 (17.4)
Far distractor tasks only (s)			
HMD + Monitor	31.6 (14.2)	33.0 (14.0)	33.5 (14.3)
Monitor only	54.8 (18.0)	52.4 (17.7)	48.7 (13.4)
Patient	87.3 (20.5)	87.5 (21.3)	104.8 (18.7)
Operating room	88.5 (23.5)	105.9 (23.2)	118.6 (21.8)
Frequency of changes in gaze location (changes/min)	4.9 (0.3)	4.3 (0.2)	4.5 (0.2)
Percentage of time looking toward a location (mean percentage of scenario duration)			
Anesthesia machine	30.1 (2.5)	24.4 (1.6)	25.6 (1.8)
Patient	41.3 (2.3)	47.7 (1.7)	47.1 (2.0)
Other	28.6	27.9	27.3

See text for comparisons reaching significance. Standard deviations are shown in parentheses.

RESULTS

Experiment 1—Inattentional Blindness

Results for participants' event detection performance and gaze are in Table 4, and a summary of questionnaire responses is in Table 5.

Mean Number of Events Detected

There were no main effects of Display or Distractor Task Location on the number of events detected. However, there was a main effect of Event Location ($P < 0.001$) indicating that participants detected most events in the HMD + Monitor location ($\bar{X} = 5.8$ of a maximum of six events), fewer in the Monitor only ($\bar{X} = 4.9$) condition, fewer again in the Patient ($\bar{X} = 4.0$) location, and fewest in the OR ($\bar{X} = 3.3$).

Mean Event Detection Times

Figure 4 shows the mean detection times for Display, Distractor Task Location, and Event Location variables. There was no main effect of Display, but there was a marginal effect of Distractor Task Location ($P = 0.071$) and a main effect of Event Location ($P < 0.001$). Events were detected fastest in the HMD + Monitor location ($\bar{X} = 23.0$ s), less fast in Monitor only ($\bar{X} = 63.5$ s), less fast again in the Patient condition ($\bar{X} = 90.3$ s), and slowest in the OR location ($\bar{X} = 127.9$ s). The interaction between Distractor Task Location and Event Location was also significant ($P < 0.001$).

Percentage of Time Looking Toward a Location

Across the 12 participants, there were 18,214 changes in gaze location coded from 16 h 21 min of video data. There was a main effect of Gaze Location ($P < 0.001$) and scenario Phase ($P < 0.001$) on the percentage of time that participants looked toward any location, but no effect of Display. There was, however, a significant interaction between Display and Gaze Location ($P < 0.001$, Fig. 5). The Tukey HSD showed that participants spent a larger percentage of time looking toward the Patient in the HMD-Near ($\bar{X} = 47.7\%$, $P = 0.012$) and HMD-Far ($\bar{X} = 47.1\%$, $P = 0.027$) conditions compared with the Control condition ($\bar{X} = 41.3\%$). They also spent a smaller percentage of time looking toward the Anesthesia machine in the HMD-Near condition ($\bar{X} = 24.4\%$, $P = 0.027$) compared with the Control condition ($\bar{X} = 30.1\%$), but the difference between the HMD-Far ($\bar{X} = 25.6\%$) and Control conditions was not significant.

The interaction between scenario Phase and Gaze Location was also significant ($P < 0.001$, Fig. 6). The Tukey HSD showed that participants spent a larger percentage of time looking toward the Patient than toward the Anesthesia machine during the Induction, Intubation, and Draping phases ($P < 0.001$), but the differences between the two locations were not significant for the Preparation and Surgery phases.

Frequency of Changes in Gaze Location

The Tukey HSD analysis of the frequency of changes in gaze location showed that compared with the Control condition, participants moved their gaze to the monitor significantly less frequently in the HMD-Near (4.9 vs 4.3 changes/min, $P = 0.002$) and HMD-Far (4.9 vs 4.5 changes/min, $P = 0.024$) conditions.

Questionnaires

The participants' postexperiment questionnaire responses are summarized in Table 5. Half of the participants rated the Control condition without the HMD as the easiest, most preferred and the fastest

Table 5. Summary of Postexperiment Questionnaire Responses in Experiment 1 and the Number of Participants Who Reported Each Statement

Measure	Control	HMD-Near	HMD-Far
Questionnaire responses (of 12 participants)			
Easiest condition to monitor the patient under	7	5	0
Preferred condition for monitoring the patient	7	4	1
Fastest condition for noticing abnormal events	6	5	1
HMD focus setting with better clarity[a]	—	8	3
			No. of participants
What did you like about the HMD?			
Monitoring irrespective of direction of gaze or location in operating room			7
Ability to monitor patient while performing other tasks			6
Clear numbers displayed on HMD			2
Immediacy of vital signs			2
Improved ergonomics			1
More willing to be distracted when using the HMD			1
			No. of participants
What did you dislike about the HMD?			
Weight/bulk of HMD and computer equipment			8
Difficulty focusing and eye fatigue			5
Not all vital signs available on the HMD			3
Distraction from monitoring anesthesia machine			2
			No. of participants
Under what circumstances would the HMD be most useful?			
Busy cases (e.g., distractions, trauma, crises, and no help available)			5
Cases with unstable patients			3
When mobile, performing tasks, or with no help available			3
Induction and extubation			1
Awake patients			1
All cases			1

[a] One participant reported equal clarity for both focal distances on the head-mounted display (HMD).

condition for detecting abnormal events. The remaining participants overwhelmingly preferred the HMD-Near condition over the HMD-Far condition for ease of monitoring, preference for monitoring, faster event detection, and clarity of displayed text.

The general attributes of the HMD which participants liked most were the ability to monitor the patient regardless of the participant's direction of gaze or location in the OR, and the ability to monitor the patient while performing other tasks. The most frequently reported dislikes of the HMD were the weight and bulk of the HMD unit and the belt-worn computer, difficulties focusing on the displayed text, and the resulting eye fatigue.

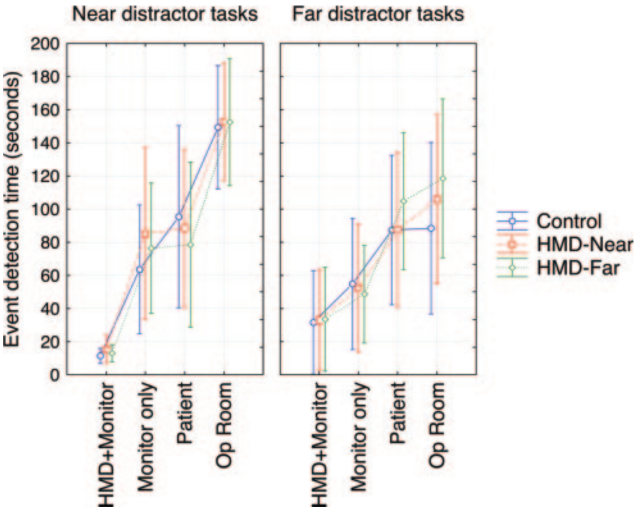

Figure 4. Event detection times in Experiment 1 for each Display condition, Distractor Task Location, and Event Location. Error bars indicate the 95% confidence interval.

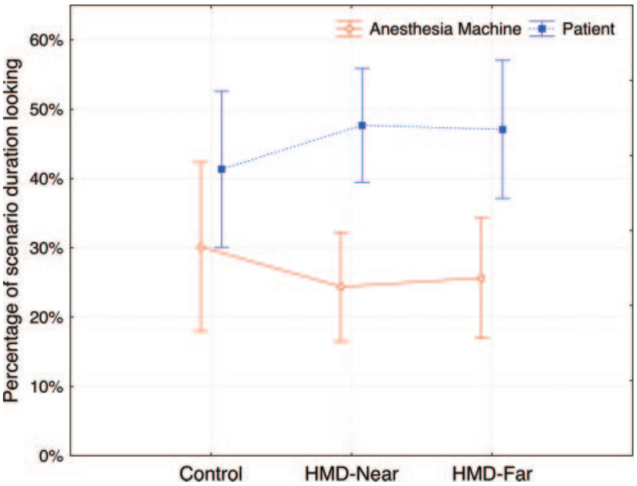

Figure 5. Proportion of scenario time in Experiment 1 that participants spent looking toward the anesthesia machine and patient in each display condition (weighted equally for each scenario phase). Error bars indicate the 95% confidence interval.

Participants reported that the HMD would be most useful for busy cases and crisis situations, cases with unstable patients, and cases during which the anesthesiologist is mobile or performing tasks.

Experiment 2—Constrained Context

The performance and behavioral results for Experiment 2 are detailed in Table 6, and a summary of the final questionnaire responses is in Table 7.

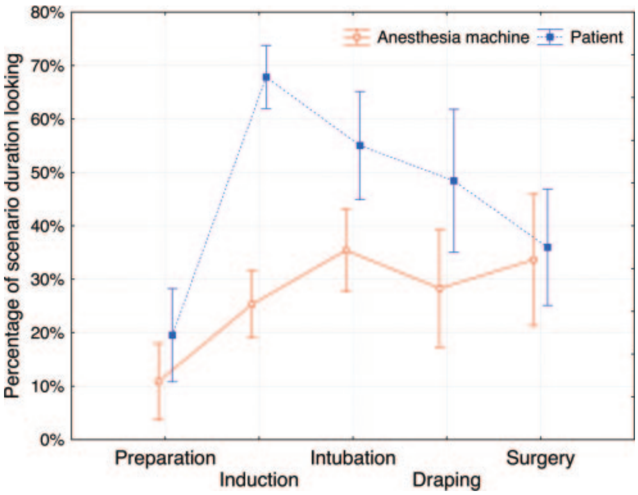

Figure 6. Proportion of scenario time in Experiment 1 that participants spent looking toward the anesthesia machine and patient in each scenario phase (weighted equally for each display condition). Error bars indicate the 95% confidence interval.

Table 6. The Performance (Unexpected Event Detection Times) and Behavioral (Monitor Scanning Patterns) Results for the Two Display Conditions in Experiment 2

Display condition	Control	HMD
Mean event detection times (s)		
Event 1 (ST depression)	69.3 (18.6)	80.3 (17.5)
Event 2 (hypoventilation)	25.7 (6.8)	77.9 (11.8)*
Event 3 (tachypnea, hypertension)	29.7 (5.0)	16.8 (3.3)*
Event 4 (hypotension)	36.3 (8.5)	13.9 (3.7)*
Frequency of changes in gaze location (changes/min)	1.5 (0.1)	0.3 (0.1)*
Percentage of time looking toward a location (mean percentage of scenario duration)		
Anesthesia machine	6.5% (0.9%)	1.0% (0.5%)*
Patient (manikin and endoscope monitor)	93.4% (0.9%)	99.0% (0.5%)*
Other	0.1%	0.0%

* Statistically significant differences between Control and HMD conditions. Standard deviations are shown in parentheses.

Mean Event Detection Times

There was a main effect of Event for the event detection times ($P < 0.001$) but no main effect of Display. However, there was a significant interaction between Event and Display ($P = 0.001$, Fig. 7). Planned comparisons showed that participants detected Event 3 (tachypnea and hypertension) (16.8 s vs 29.7 s, $P = 0.034$) and Event 4 (hypotension) (13.9 s vs 36.3 s, $P = 0.019$) faster with the HMD than in the Control condition. However, participants were slower at detecting Event 2 (hypoventilation) with the HMD (77.9 s vs 25.7 s, $P < 0.001$) than in the Control condition. The difference in detection times between conditions for Event 1 (ST segment depression) was not significant (80.3 s vs 69.3 s).

Table 7. Summary of Postexperiment Questionnaire Responses in Experiment 2

Questions/answers	Control	HMD
Postexperiment questionnaire responses (scale 1–7)		
How busy were you? (7 = busy)	5.58 (0.23)	5.25 (0.18)*
How easy was it to monitor the patient? (7 = easy)	3.58 (0.31)	5.42 (0.31)*
How quickly did you detect changes in vital signs? (7 = fast)	3.83 (0.30)	5.00 (0.30)*

	No. of participants
What did you like about the HMD?	
Ease of viewing/not having to turn around	9
Immediacy of vital signs	2
Helped concentration with maze task	1

	No. of participants
What did you dislike about the HMD?	
Weight/bulk of HMD and computer equipment	4
Headaches	2
Not all vital signs available on the HMD	2
Distraction from maze task	1
Eye discomfort	1

	No. of participants
Under what circumstances would the HMD be most useful?	
Performing tasks where the monitor is out of view	6
Busy cases (e.g., trauma, emergency, crises, no help available)	5
Procedures with invasive monitoring	1

Participants rated the display conditions on a Likert scale from 1 to 7, and provided free-form answers about their likes and dislikes of the head-mounted display (HMD).

* Statistically significant differences between Control and HMD conditions. Standard deviations are shown in parentheses.

Percentage of Time Looking Toward a Location

There was a main effect of Gaze Location ($P < 0.001$) for the percentage of time looking toward a location, no main effect of Display, and a significant interaction between the Gaze Location and Display ($P < 0.001$). Participants in the HMD conditions spent a larger percentage of time looking toward the Patient (99.0% vs 93.4%) and less time toward the Anesthesia machine (1.0% vs 6.5%) than they did in the Control condition.

Frequency of Changes in Gaze Location

There was a main effect of Display for the frequency of changes in Gaze Location ($P < 0.001$).

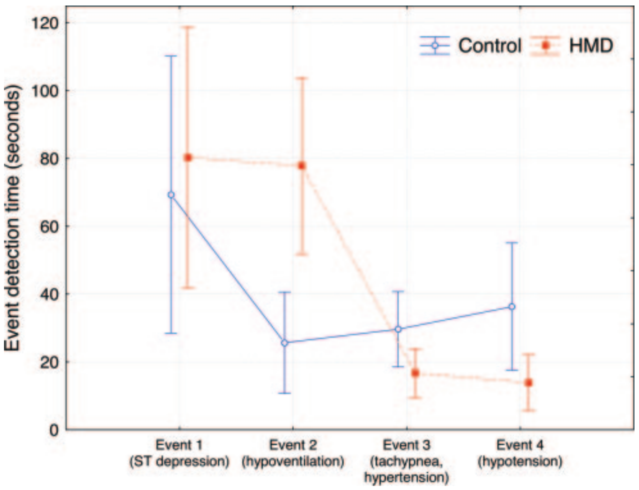

Figure 7. Event detection times in Experiment 2 for each Display condition and Event. Error bars indicate the 95% confidence interval.

Participants moved their gaze to the Anesthesia machine significantly less frequently in the HMD condition than in the Control condition (0.3 vs 1.5 changes/min).

Questionnaires

Table 7 summarizes the participants' responses to postexperiment questionnaires. They rated the scenario in which they used the HMD as being less busy ($P = 0.039$), easier to monitor the patient ($P = 0.001$), and they also believed they detected vital signs changes faster ($P = 0.002$) compared with the scenario with standard monitoring only. No participants reported that they detected the Excess sedation event more slowly with the HMD.

The attributes of monitoring with the HMD that participants liked were the ease of viewing (by not having to turn around), immediacy of vital signs, and being able to concentrate on the maze task better. Attributes they disliked were the weight and bulk of the HMD and associated equipment, headaches from wearing the HMD, not having all vital signs information available on the HMD, visual distraction from the maze task, and eye discomfort.

Participants reported that the HMD would be most useful when the anesthesiologist is performing tasks when the monitor is out of view, during busy cases or when no help is available, and during procedures using invasive monitoring.

DISCUSSION

We discuss the specific findings from the two experiments and the limitations of the research before turning to a discussion of broader issues raised by both experiments, and describe future areas of research.

Experiment 1—Inattentional Blindness

In contrast to a prior study, in which all unexpected events were detected faster with a HMD,[6] this study did not indicate that participants detect unexpected events faster when they wear the HMD. However, the prior study only investigated events in the HMD + Monitor location. Participants in the present study detected events in the four locations at different speeds, possibly because of the relative urgency of the events. Events in the HMD + Monitor and Monitor only locations required corrective action by the anesthesiologist to prevent harm to the patient, whereas events in the other locations (Patient, OR) tended to carry a shared responsibility with other staff and less need for immediate corrective action. The interaction between Distractor Task Location and Event Location for detection times was caused by differences in the specific events used in the scenarios.

There were no significant differences between the two focus settings on the HMD in participants' performance or their scanning patterns, but participants clearly preferred the HMD-Near condition. The best approach may be to let anesthesiologists self-adjust the focus to match their resting point of accommodation and to minimize eye strain[18,19] by using the "hyperopic" focusing technique.[19,20]

The HMD changed participants' monitor scanning patterns by letting them spend more time looking toward the patient, and less time toward the monitor. However, even though participants spent a larger percentage of time looking toward the patient and surgical field with the HMD, the fact that they did not notice events occurring at the patient or in the surgical field more effectively suggests that they may have been attending to information presented on the HMD and not to events occurring at the patient or in the surgical field.

There are other possible explanations for why the changes in participants' scanning patterns did not translate into performance differences, such as differences in the likelihood of detecting unexpected events. One explanation is that anesthesiologists' ability to detect unexpected events may be insensitive to changes in their scanning patterns. An alternative explanation is that anesthesiologists may have multiple means for maintaining vigilance that were not affected by the HMD in this experiment.

If the latter explanation is correct, and if anesthesiologists' means for maintaining vigilance are compromised by physical or operational constraints in the OR, then a HMD may help them detect unexpected events. Supporting this view, participants in Experiment 1 reported that the HMD would be most useful when they were physically and operationally constrained by what they were doing.

Experiment 2—Constrained Context

The effects of the more physically and operationally constrained conditions of Experiment 2 are evident when the behavioral results are compared with those from the less constrained scenarios of Experiment 1. Both the frequency with which anesthesiologists turned to look at the patient monitor and the percentage of time they spent looking toward it were much lower in Experiment 2 (Table 6) than in Experiment 1 (Table 4). In Experiment 2, the benefit of the HMD for monitoring was evident with the dramatic fivefold reduction in how often participants looked toward the monitor when they used the HMD.

We expected that when participants worked under the more constrained conditions event detection should be faster with the HMD, regardless of clinical significance. Participants detected the tachypnea/hypertension and hypotension events more quickly with the HMD, which was as hypothesized. Participants' slower detection of the hypoventilation event with the HMD was, however, not as hypothesized, and can be explained by three factors: inattentional blindness, perceptual differences, and overconfidence.

First, when people's attention is diverted to one task among two or more, they can exhibit "inattentional blindness" to quite striking events,[21] especially when using HMDs.[11,12] Excess sedation is the only event of the four we investigated that produced results consistent with inattentional blindness. Therefore, inattentional blindness alone cannot explain the Excess sedation results; it must be viewed in the context of several factors at work in determining the effectiveness of HMDs in anesthesia contexts.

Second, the four events on the HMD had different perceptual characteristics because of the specific patient vital signs involved (Table 3). Although the ST segment depression during Event 1 could not be detected on the HMD, there was an audible pulse oximetry cue (an ectopic beat) at the event onset, which cued some participants and equalized the conditions. In Events 3 and 4, either systolic or diastolic noninvasive arterial blood pressure numbers increased from <100 to >100 (or *vice versa*), which created a noticeable "pop out" effect on the HMD. In contrast, Event 2 involved a slow change (decrease in RR) in the cycling of a wave form that was already moving with each breath cycle, so there was no visual "pop-out".[22] However, this explanation assumes that the participant did not regularly scan the display.

Third, participants may have been overconfident in their ability to monitor vital signs changes with the HMD while attending to the intubation task. The HMD presented information that was always in their field of view, which may have given them the impression that they would unfailingly notice any changes. In the postexperiment questionnaires, participants rated their event detection as being faster with a HMD, even though this was true only for two of the four events. Moreover, no participant reported detecting the hypotension event more slowly with the HMD. Participants may have scanned the HMD less often than needed to detect higher-order changes and may have been more dependent on visual pop-out than they realized.

The above three factors would rarely occur at the same time in clinical practice. Furthermore, the inattentional blindness and perceptual factors could be overcome by a combination of training and improved display design, and the overconfidence factor could be mitigated through training.

Limitations

First, participants were unfamiliar with the HMD and may not have had sufficient time in Experiment 1 to develop new monitoring strategies to take advantage of its affordances. Second, the relatively high frequency of events in both experiments may have contributed to a degree of hypervigilance. Third, these studies only investigated the modality of information delivery and did not manipulate the displayed content or its presentation. Fourth, study participants were selected for 20/20 vision but anesthesiologists wearing large or multifocal glasses may have difficulties using the HMD. Fifth, auditory alarms were disabled in both experiments (although audible variable-tone pulse oximetry was present), which does not represent ideal or routine practice. Sixth, the immersive simulation environment may not replicate the behavior of participants using HMDs in the clinical environment; a clinical trial is needed. Finally, the physical form and weight of the HMD configuration used in the two experiments limited its practicality, but this will change as improvements in display technology will ultimately allow displays embedded in contact lenses.[23]

CONCLUSIONS

Our experiments indicate that HMDs may be most helpful to anesthesiologists during procedures where it is difficult to view a standard monitor, and as long as the display reliably attracts visual attention to important changes. In both experiments, anesthesiologists changed their scanning patterns when using the HMD, just as Ross et al.[7] reported.

In Experiment 1, anesthesiologists detected unexpected events no faster with the HMD than with the standard monitor, contrary to the findings of Via et al.[6] At the same time, the anesthesiologists missed unexpected events no more than when using the HMD than with the standard monitor, suggesting that inattentional blindness[2,11] may not be a major cause for concern in anesthesia. There were no performance or behavioral differences as a result of the near versus far focus settings of the HMD: therefore, the focal distance should be set at the wearer's resting point of accommodation to minimize eye strain.

In Experiment 2, participants detected some patient events faster with the HMD, as found by Via et al.[6] The finding that anesthesiologists working in constrained conditions may sometimes detect an event more slowly with a HMD has not been reported in prior simulator-based studies of HMDs.[6–8] The slower event detection is most probably due to a combination of inattentional blindness, perceptual characteristics of the displayed information, and overconfidence. Interestingly, this failure to detect a particular event was not reflected in subjective measures because participants believed that they detected events faster with the HMD (without being aware that the results showed otherwise for half of the events). If HMDs were to be routinely used for monitoring, it would be important to raise awareness of inadequate scanning and potential overconfidence through training.

Future Research

Future areas of research include manipulating the content and layout of information presented on the HMD, investigating other types of HMDs, and evaluating the HMD across a variety of different clinical environments.

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