Journal of Clinical Monitoring and Computing (2019) 33:1119–1127
https://doi.org/10.1007/s10877-019-00265-4

ORIGINAL RESEARCH

An exploratory clinical evaluation of a head-worn display based multiple-patient monitoring application: impact on supervising anesthesiologists' situation awareness

Paul D. Schlosser[1] · Tobias Grundgeiger[1] · Penelope M. Sanderson[2] · Oliver Happel[3]

Received: 27 September 2018 / Accepted: 23 January 2019 / Published online: 5 February 2019

Abstract

Purpose Supervising anesthesiologists overseeing several operating rooms must be aware of the status of multiple patients, so they can consult with the anesthetist in single operating rooms or respond quickly to critical events. However, maintaining good situation awareness can be challenging when away from patient bedsides or a central monitoring station. In this proof-of-concept study, we evaluated the potential of a head-worn display that showed multiple patients' vital signs and alarms to improve supervising anesthesiologists' situation awareness.

Methods Eight supervising anesthesiologists each monitored the vital signs of patients in six operating rooms for 3 h with the head-worn display, and for another 3 h without the head-worn display. In interviews with each anesthesiologist, we assessed in which situations the head-worn display was used and whether the continuous availability of the vital signs improved situation awareness. We also measured situation awareness quantitatively from six of the eight anesthesiologists, by instructing them to press a button whenever they noticed a patient alarm.

Results The median number of patient alarms occurring was similar when the anesthesiologists monitored with the head-worn display (42.0) and without the head-worn display (40.5). However, the anesthesiologists noticed significantly more patient alarms with the head-worn display (66.7%) than without (7.1%), $P = 0.028$, and they reported improved situation awareness with the head-worn display. The head-worn display helped the anesthesiologists to perceive and comprehend patients' current status and to anticipate future developments. A negative effect of the head-worn display was its tendency to distract during demanding procedures.

Conclusions Head-worn displays can improve supervising anesthesiologists' situation awareness in multiple-patient monitoring situations. The anesthesiologists who participated in the study expressed enthusiasm about monitoring patients with a head-worn display and wished to use and evaluate it further.

Keywords Patient monitoring · Remote monitoring · Head-worn display · Situation awareness

1 Introduction

In operating suites in Germany, experienced senior anesthesiologists supervise trainees and consult with colleagues who provide anesthesia to a single patient. The German system is comparable to the situation in the US, where a qualified doctor supervises multiple physician or nurse anesthetists. Given the supervising anesthesiologists' responsibility for the whole operating suite, they must be constantly aware of the status of multiple patients. This can be challenging if the supervising anesthesiologist is distant from patient bedsides or from a central monitoring station.

Supervising anesthesiologists could benefit from having continuously available information about multiple

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10877-019-00265-4) contains supplementary material, which is available to authorized users.

✉ Paul D. Schlosser
paul.schlosser@stud-mail.uni-wuerzburg.de

[1] Institute Human-Computer-Media, Julius-Maximilians-Universität Würzburg, Oswald-Külpe-Weg 82, 97074 Würzburg, Germany

[2] Schools of Psychology, ITEE, and Clinical Medicine, The University of Queensland, St. Lucia, QLD 4072, Australia

[3] Department of Anesthesia and Critical Care, University Hospital of Würzburg, Oberdürrbacher Straße 6, 97080 Würzburg, Germany

patients that they could access while moving around the operating suite. Head-worn displays (HWDs) could provide such support. HWDs are devices worn on the head that can display information on a small screen, visible no matter how the body and head are oriented [1, 2]. HWDs have already been tested in several clinical environments [3–7] but not for monitoring multiple patients. If the status of multiple patients in an operating suite is shown on an HWD, it could help supervising anesthesiologists to maintain awareness of their patients in a hands-free, mobile manner, even in sterile situations.

However, it is unclear whether clinicians could process the continuously available vital signs displayed on an HWD effectively and use them to develop situation awareness. Situation awareness refers to the perception of elements in the environment (level 1), the comprehension of their meaning (level 2), and the understanding of future implications (level 3) [8]. Situation awareness is crucial in anesthesia. For example, having good situation awareness supports the fast detection of patient deterioration and subsequent treatment [9, 10]. In the multiple patient monitoring situation described above, good situation awareness indicates that the supervising anesthesiologist knows "what is going on" in the operating rooms, and can therefore detect negative trends early, react appropriately, and prevent critical situations.

Instead of HWDs, smartphones [11], smartwatches [12], or large wall mounted screens [13] could be used to support multiple patient monitoring. However, wall mounted screens can display patient information only at one specific location. Smartphones and smartwatches are portable but at least one hand is required to use them. Additionally, both smartphones and smartwatches are unsuitable where a 'bare below the elbows' policy is in place. Compared to the devices listed above, HWDs have three unique features. First, the vital signs on an HWD are available hands-free and accessible without head or body movements which means patient monitoring is possible even while performing manual tasks. Second, HWDs do not interfere with hygiene restrictions because they are worn on the head. Third, accessing vital signs on an HWD requires very little time and thus patients can be monitored closely if required. The latter is important, because previous research has shown that critical events can be detected faster when vital signs are continuously available [14] and patient data are generally accessed more frequently when the effort is low [15].

However, the continuous availability of vital signs on the HWD could also have negative consequences. If the HWD were constantly enabled and most of the patient alarms were clinically irrelevant [16], the HWD could become a source of distraction for the wearer. In the worst case, the flood of alarms could fatigue the supervising anesthesiologists and even decrease their situation awareness.

The purpose of this proof-of-concept study was to evaluate how supervising anesthesiologists used an HWD to monitor multiple patients' vital signs in an operating suite. In particular, the purpose was to determine whether the continuous availability of vital signs and alarms on the HWD improved or worsened the supervising anesthesiologists' situation awareness, compared with solely using the central monitoring station. We assessed level 1 situation awareness quantitatively by instructing the anesthesiologists to press a push-button whenever they noticed a patient alarm. Additionally, we collected qualitative interview data to investigate the HWD's usage and its influence on level 2 and level 3 situation awareness. We hypothesized that providing an HWD in addition to the existing central monitoring station would result in a higher percentage of patient alarms being noticed, indicating improved level 1 situation awareness.

2 Materials and methods

The hospital's ethics committee was informed about the study. On 13 December 2017 we received a waiver that no ethics clearance was required. The supervising anesthesiologists gave written informed consent to participate in the study. In the following, the supervising anesthesiologists are referred to as anesthesiologists unless stated otherwise.

2.1 Participants

Eight anesthesiologists who regularly work in the role of supervisor participated in the study (seven male, age $Mdn = 37.5$ year, work experience as anesthesiologist $Mdn = 9.5$ year). Push-button data from only six anesthesiologists were used, because the battery in the push-button ran out of power for one anesthesiologist and for another the patient alarm logging was accidentally disabled. The semi-structured interviews with all eight anesthesiologists were analyzed.

2.2 Setting

The present study was conducted in a large operating suite of the University Hospital of Würzburg. The hospital is a large regional teaching hospital with 1450 beds. In the operating suite where the study took place, 15–25 surgeries are performed every day, mostly in the medical fields of urology and orthopaedics. In the operating suite, patients of all ages, physical status (American Society of Anesthesiologists [ASA] physical status classification), and acuity are treated. In each operating room, a trained anesthetist takes care of a patient. Two additional experienced senior anesthesiologists work in the role of supervisors for a total of six operating rooms. These anesthesiologists also carry out administrative

work, coordinate patients and staff, and provide immediate support in case of an emergency. Responsibilities for the different tasks are defined at the start of the shift. The anesthesiologists can observe their patients' vital signs on a central monitoring station and they can be contacted via phone by the anesthetist in an operating room.

2.3 Design

The experiment used a crossover design, with participating anesthesiologists allocated at random to one of two orders for experiencing the HWD and control conditions (4 anesthesiologists experienced the HWD condition first; four anesthesiologists experienced the control condition first). Random allocation to orders was done by pulling numbered paper tokens at random from an urn. In the control condition, anesthesiologists relied on standard monitoring equipment. In the HWD condition, anesthesiologists could use standard monitoring equipment but also wore the HWD. Only one of the two anesthesiologists in the operating suite was equipped with the HWD. The anesthesiologist with the HWD was instructed to collaborate with his colleague as usual, with no alteration in the normal division of labor. For each anesthesiologist, each monitoring condition lasted for 3 h on the same day.

The dependent variable was the percentage of patient alarms noticed by the anesthesiologists. All yellow and red alarms from the physiological monitoring systems installed in the six operating rooms were defined as alarms. On the central monitoring station, all alarms were displayed as colored text. In the operating rooms alarms were displayed the same way but only for a single patient. When an alarm occurred, an auditory signal was played at the central monitoring station and in the respective operating room. An alarm was considered to be noticed only if the anesthesiologist pressed the push-button within 10 s after the alarm occurred. The semi-structured interviews were analyzed with thematic analysis methodology (see Sects. 2.5 and 2.6).

2.4 Materials

In the HWD condition, the anesthesiologists wore a Vuzix M300 HWD (Vuzix Corporation, West Henrietta, NY, USA; Figs. 1, 2). The HWD can be mounted in front of the left or right eye. The color image display has a size comparable to a 40″ screen viewed from a 2 m distance. Because the screen can be placed in the peripheral field of view, the HWD does not obstruct the wearer's forward field of view.

We developed a custom multiple-patient monitoring application for the HWD [17]. There are two technical requirements for its usage. First, a secure WiFi network must be available. Second, the video signal of a central monitoring station must be accessible and recorded with a digital capture card. Our software then extracts the vital signs via text recognition. In the present study, we extracted the vital signs displayed on the Philips IntelliVue Information Center iX central monitoring station and sent them to the custom HWD interface. This technical approach is likely to be feasible in a wide variety of hospitals even if the digital interfaces of the monitoring system are disabled. A potential downside of our approach is that the custom monitoring software has to be adjusted every time the layout of the central station changes due to software updates or layout reconfigurations.

The HWD application showed an overview screen with vital signs and alarms from six operating rooms (Fig. 3a). The vital signs were updated every second. Using the buttons on top of the HWD (Fig. 2), the anesthesiologists could access a more detailed screen showing data from an

Fig. 1 Anesthesiologist wearing the head-worn display during the study. The green push-button attached to the anesthesiologist's shirt was used to report patient alarms

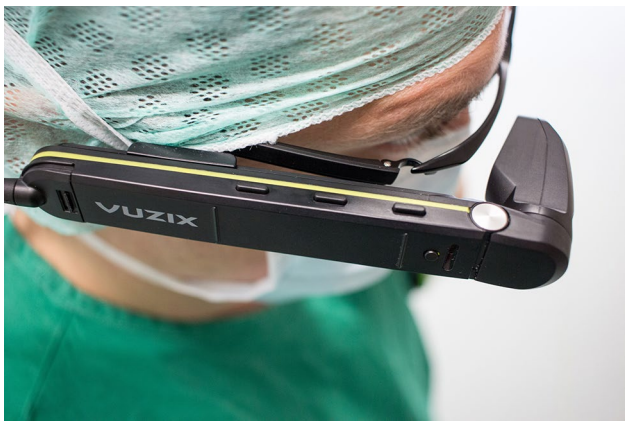

Fig. 2 Head-worn display (Vuzix M300) used in this study. The head-worn display consists of a small screen, a battery pack, and a head-mount. The patients' vital signs were displayed on the screen. The three buttons on top of the arm could be used to control the application

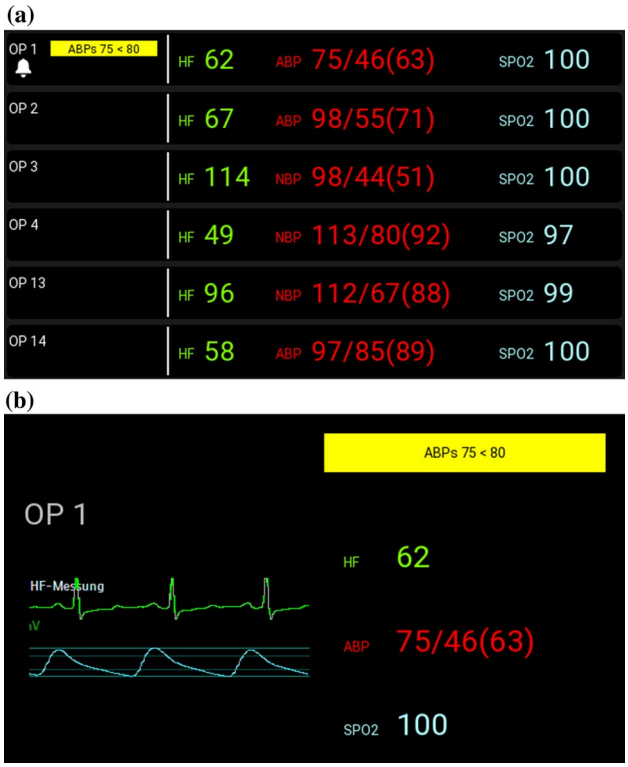

Fig. 3 Screenshots of **a** the overview screen and **b** the detail screen of the multiple-patient monitoring application. The overview screen showed the heart rate (HF), blood pressure (ABP or NBP), blood oxygen saturation (SpO2), and alarm notifications of the patients in the six operating rooms (OP). Alarm notifications appeared as colored bars (top left corner). Alarms with a low priority were displayed in yellow and alarms with a high priority were displayed in red. The detail screen showed the same information as the overview screen (HF, NBP or ABP, SpO2), plus the ECG and SpO2 plethysmography waveforms. Only one patient could be displayed at a time on the detailed screen, and a button on the head-worn display had to be pressed to cycle through the patients

individual patient in a single operating room (Fig. 3b). If an alarm was triggered for any patient, the HWD played an auditory alarm signal. The signal lasted 1 s and the pitch of the sound indicated the severity of the alarm. Alarms with a low priority (yellow alarms) were triggered when a vital sign crossed a specific threshold and were accompanied by a low pitch sound. Alarms with a high priority (red alarms) were triggered when a vital sign reached a life threatening level and were accompanied by a high pitch sound. When an alarm was sounded, the screen turned white for 150 ms, producing a flash that reliably attracts attention [18].

2.5 Procedure

The anesthesiologists were informed about the purpose of the study and the functionality of the HWD. Then the anesthesiologists were instructed to press a push-button worn over their scrubs (Fig. 1) whenever they noticed a patient alarm from any of the six operating rooms. Next, the anesthesiologists carried out their regular work for 3 h in one condition. After a break of at least 10 min, the anesthesiologists worked for 3 h in the other condition. At the end of the study, the anesthesiologists were interviewed for 20–30 min about their experience with the HWD.

The interviews covered four topics: (1) anesthesiologists' procedures for monitoring multiple patients without an HWD, (2) effect of the HWD on the monitoring, (3) the HWD's software usability and (4) reactions to the HWD hardware. The interviewer asked questions from a predefined question pool (Online Appendix 1). However, because of the exploratory nature of the study and the lack of previous research covering multiple-patient monitoring with an HWD, the anesthesiologists were encouraged to report every aspect of their experience with the HWD, even if not specifically addressed by a question. The anesthesiologists received a five Euro cafeteria voucher for their participation.

2.6 Analysis

We used Wilcoxon Signed Ranks Tests to analyze the quantitative data (SPSS 25, IBM, Chicago, IL). Alpha was set at 0.05. The qualitative data were analyzed using thematic analysis [19], which can be used to find patterns in qualitative data and to generate broader concepts inductively. Through four analytic steps, findings emerge in a 'bottom up' way [20] and are closely linked to the collected interview data [21].

First, the interviews were coded. In other words, all statements in the interviews were assigned a meaningful label. Second, the codes were grouped based on their meaning and themes were generated that covered one specific topic. Third, we checked whether all relevant codes could be assigned to the different themes and themes with few codes were merged with others. Finally, four themes were established (see the four subheadings in Sect. 3) and the connections among individual themes were analyzed.

3 Results

3.1 Usability of the HWD

All eight anesthesiologists positioned the HWD in their peripheral field of view (seven in front of the right eye) and they reported that they could easily access vital sign information while wearing the HWD (Table 1). All anesthesiologists reported that the HWD did not move on their head, but its firm fit caused pressure pain for over half the anesthesiologists. Additionally, all anesthesiologists stated that the HWD's battery cable made it more difficult and

Table 1 Anesthesiologists' opinion on different properties of the head-worn display (HWD)

Properties of the HWD	Number of reports	Opinion of the anesthesiologists
Readability	7	Vital signs could be easily read on the HWD
	1	Concentration was required while reading on the HWD
Multiple-patient monitoring interface	8	Structure of the interface was logical
	6	All required information were displayed
	6	Detail screen was seldom accessed
Fit on the head	8	HWD did not move on the head
	5	Firm fit caused pressure pain
	2	HWD's position had to be readjusted while wearing
User interaction	6	Controlling the application with the buttons was easy
	4	Wrong buttons were pressed because they were on top of the unit and therefore out of sight
Weight and size	4	HWD was too heavy and too big
Compatibility with a surgical mask	8	HWD interfered with the tie-on laces of the surgical mask

time consuming to put on a surgical mask. Half the anesthesiologists found the HWD too heavy and too big. Despite the above physical drawbacks, most anesthesiologists liked the HWD's readability and the structure of the multiple-patient monitoring application. The user interaction with the buttons was considered to be easy, but four anesthesiologists reported that they made some errors when attempting to display a specific operating room because of the button locations.

3.2 Patterns of use of the HWD

Overall, the anesthesiologists listed seven reasons why they accessed vital sign information on the HWD (Table 2). All

Table 2 Reasons why the anesthesiologists checked the head-worn display (HWD) during their work

HWD was checked because	Number of reports	Anesthesiologist's quote
A patient alarm occurred on the HWD	8	Of course [I looked at the HWD] when an alarm popped up. I think, I detected almost all of them. And then I checked what the problem was
The anesthesiologist had some spare time	7	I was relatively frequently looking at it [the HWD] and also checked vital signs that did not trigger an alarm. And I realized that there were low values that did not set off an alarm, yet
There were critical patients in the operating rooms	7	We had two patients that were not completely stable. I checked their current status frequently on it [the HWD]
The operating rooms were not utilized efficiently	6	One is also involved in utilizing the operating rooms efficiently. And [with the HWD] I could see whether one patient was already in the operating room. Because of this, I checked 1–2 times why a surgery had not been started yet. I could see that there were no vital signs of the patient in the operating room
An anesthesiologist in an operating room consulted the supervising anesthesiologist (wearing the HWD) via phone	2	It [the HWD] helped me, when I was being called because of a patient. Someone asked me something about his current patient and I could inform myself about the patient's status and assess the situation better on the phone
The anesthesiologist could not leave one operating room for a prolonged time	2	When I knew that I would not be able to leave an operating room for the next minutes, I looked at the HWD occasionally and checked that all other patients were safe, and everything was alright
The anesthesiologist treated a patient and required his/her vital sign information	1	We were preparing the emergence of a child from general anesthesia in one operating room and I saw the vital signs twice [both on the HWD and the standard monitoring]. But it was not disturbing. I could turn away from the child, but I could still see what was going on

anesthesiologists looked at the HWD when a patient alarm occurred, but they occasionally looked at the HWD when there were no alarms also. The anesthesiologists checked the HWD when they could not leave an operating room for a prolonged time, when a patient with high ASA classification underwent surgery, or when another anesthesiologist called from an operating room and asked for assistance. Anesthesiologists also checked the occupancy of the operating rooms with the HWD. When the HWD showed no vital signs for an operating room, the anesthesiologists could infer either that the case in that operating room was still to start, that it was ending, or that the schedule of the day for that operating room was completed, depending on context. One anesthesiologist reported that the HWD was useful during treatment of a patient to access vital signs when the conventional patient monitor was out of sight.

Seven anesthesiologists reported that they at least once acted in a certain way because of information displayed on the HWD. Table 3 presents two potentially critical situations in which an anesthesiologist intervened due to information provided by the HWD. However, it was also noted that the information on the HWD was limited and not always sufficient for clinical decision-making.

3.3 Distraction

During low workload situations, such as when walking from one operating room to another or when routinely checking the status of a patient, most anesthesiologists did not perceive the auditory alarms of the HWD to be distracting (no anesthesiologist mentioned the simultaneous flash). Three anesthesiologists stated that the distraction was not severe because hearing an alarm sound and then checking the HWD did not require much time. The anesthesiologists noted that phone calls were more distracting than the HWD alarms, because the former consumed more time and mental resources.

During high workload situations, such as when intubating a patient or placing a central venous catheter, the anesthesiologists found the alarms of the HWD distracting. However, the degree of perceived distraction varied between individuals. One anesthesiologist reported that he could easily perform anesthetic procedures while checking the alarms on the HWD. Another reported that, with the HWD, he felt that he could not focus 100% of his attention on a patient while treating him/her. Additionally, three anesthesiologists felt that the HWD reduced their field of view slightly during specific procedures. Two anesthesiologists shifted the HWD upwards out of their visual field during a demanding manual task. However, both anesthesiologists stated that with more experience with the HWD they might feel more comfortable using it during anesthetic procedures.

Despite the distraction caused by the HWD, six anesthesiologists said that before the study they had been skeptical of monitoring patients with an HWD. After having used the HWD, five anesthesiologists said that they would like to further test or regularly use the HWD.

Table 3 Situations in which anesthesiologists based their actions on information of the head-worn display (HWD)

Description of the situation	Anesthesiologist's quote
The oxygen saturation of a patient dropped while she emerged from general anesthesia. The situation was detected by the anesthesiologist with the HWD before he was alarmed via phone and the patient could be extubated safely	There was one situation, in which I saw [on the HWD] that the oxygen saturation of a patient dropped to 80%. I immediately walked to this patient. When I arrived, the saturation already was back to a lower normal range and the junior anesthetist wanted to extubate her. This wouldn't have gone well, because of remaining respiratory depression and sedation due to opioids and I decided to antagonize her first. […] And I have to say, I would have not been able to recognize it that fast [without the HWD] and if I hadn't, we maybe would have had to reintubate her. It really helped me to anticipate and prevent a potentially critical situation
The systolic blood pressure of a patient was measured incorrectly. This was detected on the HWD and could be solved in the operating room	I called one operating room because [I saw on the HWD that] the blood pressure of one patient was odd and I said: "Hey, this blood pressure does not look right. It looks subdued. Your arterial line must be blocked. The systolic blood pressure is way higher." He then flushed the catheter, and this was it [the problem]

3.4 Situation awareness improvements

The quantitative data showed that the anesthesiologists noticed a significantly larger percentage of patient alarms in the HWD condition, for a median [IQR] of 66.7% [53.1%, 93.1%] compared with the control condition, 7.1% [4.7%, 8.8%], $P = 0.028$. The anesthesiologists noticed more potentially relevant information with the HWD than without the HWD (level 1 situation awareness).

The median [IQR] number of patient alarms occurring within the 3-h periods in the HWD condition, 42.0 [33.3, 45.3] and in the control condition, 40.5 [34.5, 60.3] showed no significant difference, $P = 0.753$. The median [IQR] time required by the anesthesiologists to detect and report an alarm in the HWD condition, 4.07 s [3.26 s, 4.91 s] and in the control condition, 4.12 s [0.71 s, 6.63 s] showed no significant difference, $P = 0.917$.

The qualitative data are not sufficient to draw conclusions about level 2 and level 3 situation awareness. However, in the interviews all anesthesiologists stated that the HWD supported them in comprehending their environment (level 2 situation awareness). Seven anesthesiologists said that they could make assessments more conveniently with the HWD than without it. For example, a supervising anesthesiologist received a phone call from one of the operating rooms with a question concerning the patient's current status. He could answer the question by accessing the patient's vital signs on the HWD, analyzing the situation and then giving his opinion. In addition, the fact that six anesthesiologists could infer the end of a procedure in an operating room from the absence of vital sign data on the HWD indicates that the HWD helped the anesthesiologists to understand their environment better. Finally, four anesthesiologists explicitly said that the HWD helped them "to understand what was going on [in the unit]".

Seven anesthesiologists also stated that the HWD affected their future actions (level 3 situation awareness). For example, anesthesiologists noticed the deterioration of vital signs on the HWD before alarm thresholds were crossed and thus could intervene at an early stage. One anesthesiologist explicitly said that the HWD helped him to anticipate a critical situation (Table 3).

4 Discussion

Our study has shown that when supervising anesthesiologists wore an HWD that made patients' vital signs continuously available, it improved their awareness of alarms, compared with relying only on the central surveillance monitor. The interview data revealed multiple situations in which anesthesiologists used the HWD to access information and make decisions. The quantitative data support the conclusion that the HWD improved level 1 situation awareness. However, solely perceiving patient alarms on an HWD is not sufficient for attaining good level 1 situation awareness in the complex work environment of anesthesiologists. In fact, it is important for anesthesiologists to perceive as many relevant stimuli in the clinical environment as possible to know what is going on in the unit. The qualitative interview data contain preliminary indications that the HWD might also promote level 2 and level 3 situation awareness. For example, anesthesiologists noticed or anticipated potentially critical situations because they could access alarms and vital signs on the HWD. Overall, we believe that HWDs could be a valuable addition to existing monitoring equipment, helping anesthesiologists to stay aware of patients' status, to make informed decisions, to set priorities dynamically, and even to check the occupancy of the operating rooms.

Although the HWD improved situation awareness, it also distracted the anesthesiologists during demanding manual procedures. The problem may be caused by the auditory alarm signals rather than by the visual representation of the vital signs on the HWD, because sounds attract attention exogenously [22] and are thus harder to ignore. The distraction may be reduced by rotating the HWD display screen out of view during demanding procedures or by implementing an HWD-mute function that would disable all audio alarms. This might be crucial, as the distraction induced by the audio alarms might outweigh the situation awareness benefits of the HWD. To evaluate the quality of future HWDs with mute-functionality, it will be important to find ways to measure and compare the positive and negative effects of HWDs on situation awareness.

The study has several limitations. First, we did not measure situation awareness quantitatively using a standard method, such as the Situation Awareness Global Assessment Technique [8] or the Situation Present Assessment Method [23]. Both methods were considered too intrusive to use in a busy operating suite. The push-button was a relatively non-intrusive way to measure one aspect of the anesthesiologists' situation awareness (level 1 situation awareness). In principle, the anesthesiologists could have pressed the push-button whenever they heard an acoustic alarm from the HWD without further evaluating the alarm on the screen. However, this is unlikely the case because all anesthesiologists reported in the interviews that they did evaluate patient alarms on the HWD after noticing them. Second, the number of participants in the study was small. More participants could have contributed further observations and insights to the qualitative data. Third, the anesthesiologists may have noticed more alarms in the HWD condition in order to perform "well" in the study or because the HWD was novel and the anesthesiologists were motivated to use it. Fourth, the presence of the HWD in the HWD condition might have kept the anesthesiologists aware of their participation in a

study and reminded them to press the push-button when an alarm occurred. In other words, the HWD might have acted as a prospective memory cue [24] that was only available in one of the experimental conditions. In the control condition, anesthesiologists might have detected more alarms than they reported, but forgot to report them due to the missing prospective memory cue in form of the HWD. However, it is unlikely that the prospective memory cue had a major effect on the results. We analyzed precisely when the anesthesiologists reported alarms. The reports were evenly distributed over the whole period of the experiment. If the anesthesiologists had forgotten the instruction to press the push-button over the course of the experiment, the number of alarm reports would have significantly decreased over time, which was not the case. Wearing the push-button on their shirts and carrying the walkman sized transmitter might in themselves have been sufficient to remind the anesthesiologists of their task in the control condition, reducing the likelihood that wearing the HWD was a confounder.

5 Conclusion

In conclusion, this study demonstrates that monitoring multiple patients with a mobile HWD is possible and could be a good addition to stationary central monitoring stations. The quantitative data collected during the study suggest that the HWD improved the anesthesiologists' perception of the environment (level 1 situation awareness). The qualitative interview data contain preliminary indications that the HWD might also improve the anesthesiologists' comprehension of the environment and projection into the future (level 2 and level 3 situation awareness). The HWD helped the anesthesiologists to make patient assessments and anticipate critical situations. The anesthesiologists found the HWD especially useful when they could not leave an operating room for a prolonged time or during patient treatment when the conventional patient monitors were out of sight. On the other hand, the auditory alarms of the HWD distracted the anesthesiologists while they were performing demanding manual procedures.

Future research should investigate the influence of the HWD on level 2 and level 3 situation awareness in more detail and consider the potentially negative impact of many nuisance alarms on the HWD. Advanced display design will be required to prevent anesthesiologists from suffering alarm fatigue [25] and hardware that is more comfortable to wear is needed to allow prolonged use of the HWD. Furthermore, we must analyze how the HWD affects the work of the anesthesiologist's colleagues and patients so as to avoid unintended consequences in the complex socio-technical system of the operating suite. Overall, the present research lays a foundation for more advanced HWD based multiple-patient monitoring applications to support supervising clinicians' situation awareness and to investigate ways to minimize unwanted distraction.

Acknowledgements The authors thank Dr. Michael Neumann, Dr. Frank Kobelt, and the other members of the SMI team of the University Hospital of Würzburg who helped to integrate the HWD into the hospital's IT systems for their great support.

Funding The authors declare that they have not received any funding for their research.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. The hospital's ethics committee was informed about the study and on 13 December 2017 we received a waiver that no ethics clearance was required.

Informed consent was obtained from all individual participants included in the study.

References

1. Azuma RT. A survey of augmented reality. Presence: Teleoper Virtual Environ. 1997;6(4):355–85. https://doi.org/10.1162/pres.1997.6.4.355.
2. Cakmakci O, Rolland J. Head-worn displays: a review. J Displ Technol. 2006;2(3):199–216. https://doi.org/10.1109/JDT.2006.879846.
3. Liu D, Jenkins SA, Sanderson PM. Patient monitoring with head-mounted displays. Curr Opin Anesthesiol. 2009;22(6):796–803. https://doi.org/10.1097/ACO.0b013e32833269c1.
4. Muensterer OJ, Lacher M, Zoeller C, Bronstein M, Kübler J. Google glass in pediatric surgery: an exploratory study. Int J Surg. 2014;12(4):281–9. https://doi.org/10.1016/j.ijsu.2014.02.003.
5. Yoon JW, Chen RE, Han PK, Si P, Freeman WD, Pirris SM. Technical feasibility and safety of an intraoperative head-up display device during spine instrumentation. Int J Med Robot. 2017;13(3):e1770. https://doi.org/10.1002/rcs.1770.
6. Kolodzey L, Grantcharov PD, Rivas H, Schijven MP, Grantcharov TP. Wearable technology in the operating room: a systematic review. BMJ Innov. 2017;3(1):55–63. https://doi.org/10.1136/bmjinnov-2016-000133.
7. Dougherty B, Badawy MS. Using google glass in nonsurgical medical settings: systematic review. JMIR Mhealth Uhealth. 2017;5(10):e159. https://doi.org/10.2196/mhealth.8671.
8. Endsley MR. Toward a theory of situation awareness in dynamic systems. Hum Factors. 1995;37(1):32–64. https://doi.org/10.1518/001872095779049543.
9. Gaba DM, Howard SK, Small SD. Situation awareness in anesthesiology. Hum Factors. 1995;37(1):20–31. https://doi.org/10.1518/001872095779049435.
10. Schulz CM, Endsley MR, Kochs EF, Gelb AW, Wagner KJ. Situation awareness in anesthesia concept and research.

Anesthesiology. 2013;118(3):729–42. https://doi.org/10.1097/ALN.0b013e318280a40f.
11. van Ettinger M, Lipton J, Nelwan S, van Dam T, van der Putten N. (2010) Multimedia paging for clinical alarms on mobile platforms. Proceedings of the Conference on Computing in Cardiology. p. 57–60.
12. McFarlane DC, Doig AK, Agutter JA, Brewer LM, Syroid ND, Mittu R. Faster clinical response to the onset of adverse events: a wearable metacognitive attention aid for nurse triage of clinical alarms. PLoS ONE. 2018;13(5):e0197157. https://doi.org/10.1371/journal.pone.0197157.
13. Görges M, Westenskow DR, Markewitz BA. Evaluation of an integrated intensive care unit monitoring display by critical care fellow physicians. J Clin Monit Comput. 2012;26(6):429–36. https://doi.org/10.1007/s10877-012-9370-0.
14. Pascale MT, Sanderson P, Liu D, Mohamed I, Brecknell B, Loeb RG. The impact of head-worn displays on strategic alarm management and situation awareness. Hum Fact. 2019. https://doi.org/10.1177/0018720818814969.
15. Yang XJ, Wickens CD, Park T, Fong L, Siah KTH. Effects of information access cost and accountability on medical residents' information retrieval strategy and performance during prehandover preparation: evidence from interview and simulation study. Hum Factors. 2015;57(8):1459–71. https://doi.org/10.1177/0018720815598889.
16. Sendelbach S, Funk M. Alarm fatigue: a patient safety concern. AACN Adv Crit Care. 2013;24(4):378–86.
17. Schlosser P, Grundgeiger T, Happel O. (2018) Multiple patient monitoring in the operating room using a head-mounted display. Proceedings of the CHI Conference extended abstracts on human factors in computing systems. p. 1–6. https://doi.org/10.1145/3170427.3188460.
18. Jonides J. Voluntary versus automatic control over the mind's eye's movement. Atten Perform IX. 1981;9:187–203.
19. Braun V, Clarke V. Using thematic analysis in psychology. Qual Res Psychol. 2006;3(2):77–101. https://doi.org/10.1191/1478088706qp063oa.
20. Boyatzis RE. Transforming qualitative information: thematic analysis and code development. Thousand Oaks: Sage Publications, Inc; 1998.
21. Patton MQ. Qualitative evaluation and research methods. 2nd ed. Thousand Oaks: Sage Publications, Inc; 1990.
22. Sanderson P. The multimodal world of medical monitoring displays. Appl Ergon. 2006;37(4):501–12. https://doi.org/10.1016/j.apergo.2006.04.022.
23. Durso FT, Hackworth CA, Truitt TR, Crutchfield J, Nikolic D, Manning CA. Situation awareness as a predictor of performance for en route air traffic controllers. Air Traffic Control Q. 1998;6(1):1–20. https://doi.org/10.2514/atcq.6.1.1.
24. McDaniel MA, Einstein GO. Prospective memory: an overview and synthesis of an emerging field. Thousand Oaks: Sage Publications, Inc; 2007.
25. Graham KC, Cvach M. Monitor alarm fatigue: standardizing use of physiological monitors and decreasing nuisance alarms. Am J Crit Care. 2010;19(1):28–34. https://doi.org/10.4037/ajcc2010651.