Augmented Reality as a Countermeasure for Sleep Deprivation

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Abstract—Sleep deprivation is known to have serious deleterious effects on executive functioning and job performance. Augmented reality has an ability to place pertinent information at the fore, guiding visual focus and reducing instructional complexity. This paper presents a study to explore how spatial augmented reality instructions impact procedural task performance on sleep deprived users. The user study was conducted to examine performance on a procedural task at six time points over the course of a night of total sleep deprivation. Tasks were provided either by spatial augmented reality-based projections or on an adjacent monitor. The results indicate that participant errors significantly increased with the monitor condition when sleep deprived. The augmented reality condition exhibited a positive influence with participant errors and completion time having no significant increase when sleep deprived. The results of our study show that spatial augmented reality is an effective sleep deprivation countermeasure under laboratory conditions.

Index Terms—Spatial augmented reality, sleep deprivation, procedural task performance

1 Introduction

Estimations are that 16% of the Australian and up to 30% of the United States workforces are employed in shift work [16, 30]. This significant population is at risk of reduced cognitive performance due to sleep restriction [13, 19, 20]. A number of studies have provided evidence for the negative impact of shift work on such issues as neurocognitive functioning [14], worker productivity [17] and workplace safety [49]. Other evidence indicates that the frequency of negative outcomes rises with increasing time-on-task and hours at work [11].

Sleep deprivation is one factor shown to increase negative consequences including reduction of job performance and higher propensity for error [14, 23]. This is especially true for tasks that involve monotony or unpredictable duration whilst still requiring accurate and efficient performance. For this reason, they can be especially susceptible to sleepiness [23]. Deprived of the important recuperative properties of sleep, people typically experience deteriorations of working memory, response inhibition and problem solving. Some of these effects can be observed after a period of only sixteen hours of wakefulness [52].

Methods of combatting these effects are widely investigated, but there are currently a limited set of countermeasures. The term countermeasure is defined as an intervention that negates or reduces the effects of sleep deprivation. Existing countermeasures are primarily caffeine and pharmaceutical stimulants [10, 31, 38], napping [32], exercise [17, 45], breaks [13], and environmental manipulation [4, 6]. Each existing countermeasure has a unique set of limitations, and they are not always appropriate for all users and work conditions. The key goal of this paper is to explore AR as a *new* sleep deprivation countermeasure.

Many applications of AR technology have been shown as effective methods of increasing user focus and performance while completing tasks [48]. Domains such as manufacturing and design [33], the military [28], transportation and medicine [18] have shown the use of AR for guidance and instruction to be beneficial when compared to more traditional methods.

AR works by presenting computer-generated imagery in concert with a user's view of the physical world [1]. The ability provided by AR to simultaneously view both real and virtual information removes the disconnect when a user attends to a task and information located elsewhere, referred to as divided attention [27]. One theory is that AR reduces cognitive demand [26] required for task completion when guidance and instruction is provided in situ with AR rather than on a nearby paper manual or monitor. For practical use in the aforementioned domains, if shown to be true, AR has the potential to maintain user performance when forced to function under sleep deprived conditions. To date, the use of AR on sleep deprived users has not been explored.

A straightforward experimental design was chosen to test the impact of sleep deprivation on procedural task performance. The experiment was performed under the strict protocols and laboratory conditions of the Centre for Sleep Research (CfSR) at the University of South Australia. The design involved six testing points throughout the course of a night while the participants stayed awake. The procedural task is a simple button pressing task designed to approximate the interaction with a control panel, commonly seen on a factory floor. The use of a simple task, tested at multiple time points, enabled an exploration of the compounding effects of sleep loss.

This research makes three contributions to AR and psychology of sleep literature. No study to date has examined the use of AR for task performance with sleep deprived users. Our investigation showed that users maintained consistent performance while sleep deprived when using SAR as an instructional medium. The findings indicate that SAR is a sleep deprivation countermeasure for procedural tasks. This research will offer an alternative to current countermeasures (napping, stimulants and environmental manipulation) when the current techniques are not feasible or effective. The contributions of this paper can be summarized as follows:

1. Conducted a sleep study to investigate the effectiveness of SAR technology.
2. Our study shows that SAR is an effective sleep deprivation countermeasure under laboratory conditions.

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3. SAR has the potential to be applied as a sleep deprivation countermeasure for procedural tasks in industry settings.

The remainder of this paper includes an overview of the relevant research into AR and SAR technology and annotations, and sleep deprivation. This background is followed by the description of a user study examining the use of our annotations. The results of the experiment and the practical applications are discussed. The paper is finished with a set of concluding remarks.

2 Background

This section provides an overview of AR and SAR technologies that pertain to our investigation. A synopsis of relevant sleep deprivation research is provided to place our research in context of the wider sleep research domain. An overview is provided of the use of AR for user task improvement in three application domains: manufacturing, the military and medicine.

2.1 Sleep Deprivation

Sleep is imperative for bodily restoration including the brain and is essential to cognitive processing. Electrophysiological investigations have discovered that patterns of neuromodulatory activity and electric field potential oscillations particular to slow-wave sleep (SWS) promote system consolidation while patterns specific to rapid eye movement (REM) sleep promote synaptic consolidation [8]. Walker [50] indicates that sleep plays a significant function in emotional processing and homeostasis. Reducing sleep has consequences that influence affect and mood impacting cognitive performance during wakefulness.

Proper sleep patterns are critical for cognitive performance, as demonstrated by studies that have manipulated sleep or examined populations with sleep disorders and especially shift workers. Dawson and McCulloch's review of laboratory study results exploring the effects of total and partial sleep loss on cognitive performance found that "clinically significant" loss of performance is observed when sleep is limited to below five to six hours [7]. Van Dongen et al. [46] explored the impact of eight hours, six hours and four hours in bed for 14 days on cognitive performance. In addition to performance decrements, they also report after 14 days in the six hours in bed condition performance was equivalent to someone with two full nights of sleep deprivation. The latter exemplifies the influence of even slight sleep restriction on performance and highlights the concern as to the impact of sleep loss on task performance in critical activities.

The pre-frontal cortex is recognized to be particularly active during wakefulness and evidence from neurophysiological studies indicates that it is especially susceptible to sleep deprivation [14]. It is responsible for synchronising activities that involve a user's working memory, response inhibition and set shifting (otherwise known as executive function). Working memory constitutes the transient holding and processing of new and already-stored information and has been shown to be critical for human computer interaction [19].

Affected sleep patterns are a widespread aspect of shift work. Working non-standard hours can result in a person pursuing sleep when their body is primed to be active and, conversely, attempting to continue to be attentive when their body is primed for sleep. The interplay between sleep/wake history and circadian timing regulates a person's cognitive performance. For example, sleepiness is heightened due to an extended period of wakefulness and during particular periods of the day, such as between 0200h-0600h. During these periods fatigue is high and cognitive performance is dramatically impaired [3].

A number of countermeasures have been investigated to address performance and safety issues as a result of performing shift work. The most well examined countermeasure is the application of stimulants, especially caffeine. Caffeine has been shown to have positive effects on alertness and performance at low to moderate doses. Repeated consumption is linked with tolerance, and larger doses may be associated with tension, anxiety and sleeping problems [10]. Pharmacological agents such as methylphenidate and modafinil have been reported to enhance cognitive performance in healthy shift workers [31]. There are long term safety concerns, and the habituation of the pharmacological agents will limit their effectiveness [38]. A person taking a nap (short sleeping session) is a possible replacement countermeasure to pharmacological agents. Napping has been reported to improve alertness and performance [35], but it can lead to sleep inertia with resulting negative effects on performance and safety [32]. Activity and/or rest breaks are also useful in reducing the effects of fatigue in shift workers [17, 45]. Improved lighting and acoustics in the workplace has been reported to be successful in promoting alertness for shift workers [6, 4]. The most commonly employed workplace intervention (but due to practicality issues the least well investigated method for dealing with the influence of shift work on performance) has been to adjust shift schedules and rosters such that they best support rest and sleep [13]. Regardless of the advantages of the countermeasures to date, new countermeasures are required, particularly those that can minimize the influence of reduced executive function on task performance.

2.2 Augmented Reality

AR supplements the physical world with registered computer-generated imagery and information to enhance a user's experience [1]. AR achieves this by employing technology such as head-mounted displays (HMDs) to provide a window through which a user can see both the physical world and registered computer-generated visualizations [39]. By employing this combination of actual and virtual information, AR resolves many of the limitations suffered by virtual reality, most notably that all information provided to the user in virtual reality is purely virtual and is disconnected from the physical world. This ability allows for users of an AR system to interact with objects in the physical world, but have the appearance altered or additional information for these objects provided by the AR software.

Afforded by its method of presentation, AR has a number of unique uses. Instruction and guidance for the learning and performing of tasks is particularly suited to AR [26]. Placing the instructional information directly onto the object of focus means that there is no disconnect between the task and the guidance. Studies have shown this to have a positive effect on both the learning outcomes and overall performance and task completion times [20, 25, 29].

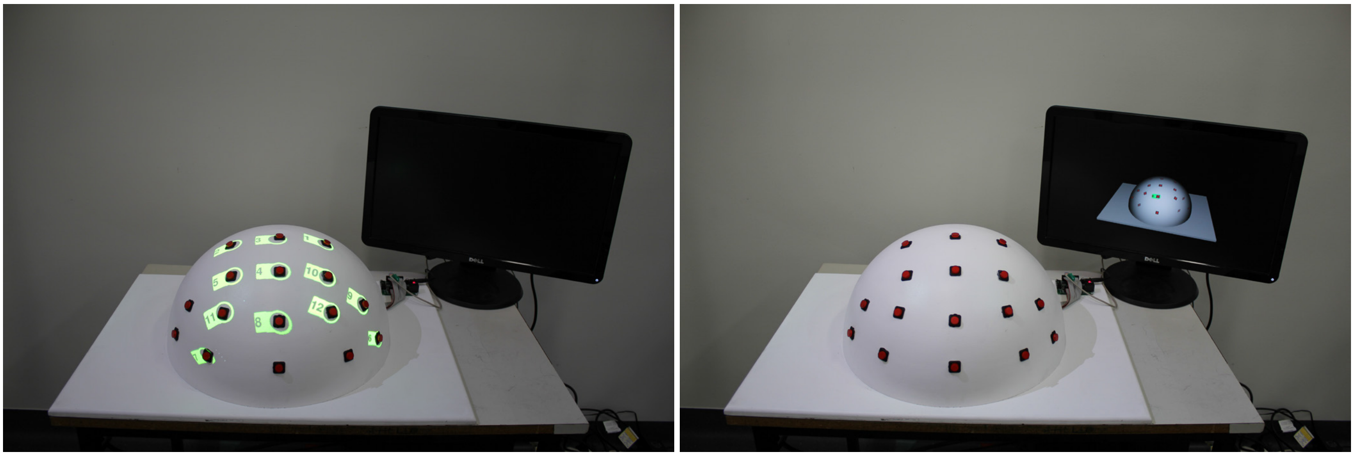
SAR affords the same interaction with the physical world as AR, but addresses some limiting factors of HMDs by using projectors [36] to illuminate the surfaces of objects, thereby altering their appearance. In addition, the visualizations can be coupled with six degrees-of-freedom tracking to ensure that they are viewed with correct perspective [5, 37]. One major benefit of SAR presentation is that multiple users may view the same information and from any angle, and since the users do not wear any devices, communication is more natural.

2.3 Applications of Augmented Reality

The following subsection provides an overview of AR's use within three domains: manufacturing, the military and medicine. These have been chosen as they represent areas in which AR's potential for benefit is high, and they are areas in which professionals may need to maintain prolonged focus despite suffering effects of sleep deprivation.

As a first step toward implementing AR within factories and manufacturing plants, several studies have examined its instruction efficacy for simple object assembly tasks. Sääski et al. [40] conducted a pilot test on a prototype HMD-based AR system designed to instruct the assembly of a tractor part. The system was an extension to preliminary tests conducted using a 3D puzzle that showed AR to have a positive effect. Henderson and Feiner [25] took this investigation further and had participants complete a procedural task involving the assembly of a combustion chamber. The authors found that the AR instructions were more helpful than the monitor documentation and that the users reported a preference for the AR condition.

Tang et al. [44] examined the effectiveness of instructions provided with an LCD monitor versus as AR on an optical see-through HMD. While the authors did show that their AR condition significantly improved both completion time and errors rates as compared to a paper display, when compared to the monitor condition on completion time, no significant effect was found. Results of their workload analysis using the NASA TLX indicated that AR's performance and error



(a) Instructions shown all at once with 12 presses using SAR to identify the order.

(b) Instructions shown per button press using a traditional monitor.

Fig. 1: Experimental conditions using SAR and a traditional monitor.

improvements may be attributable to lower cognitive demands placed upon the users. The Marner et al. [29] study compared performance with SAR versus monitor-based instructions, and they found SAR provided improvement in procedural task performance in both completion time and number of errors.

Projector technology has also been used in a similar manner for the guidance of spot welding in the automotive sector, enabling the workers to focus solely upon their welding task as they no longer need to refer to a nearby schematic diagram. Projector guidance is particularly suitable for this form of instruction as workers can complete their welds unhindered by imaging technology, such as an HMD. Schwerdtfeger et al. [42] found that when users were given the option between a head-worn projector and a mounted projector, the mounted projector was preferred. Zaeh and Vogl [53] used laser projectors to program the function of an industrial robot. Using their interface, a user defined a path with a tracked input device. The robot would then follow the tracked trajectory, performing its task along that route. The authors found the interactivity gains granted by the use of SAR techniques produced a reduction of up to 80% in robot programming time, when compared to the user's ordinary method.

Military applications are another domain where researchers are exploring the use of AR technologies. Peak decision making and task performance are required of deployed operators in military environments. The limited research that has been conducted on the incorporation of AR guidance into military operations indicates that it is an area of great potential. In a study conducted on the maintenance of an armored personnel carrier turret, Henderson and Feiner [24] compared performance between HMD AR-based and monitor-based instructions. Participants in their study were instructed to perform maintenance tasks on the personnel carrier. The results showed that the AR guidance led to significantly faster task location than the screen condition. In addition, head tracking data showed significantly less head rotation and movement.

Virtual environments, including AR, in the field of medicine have received much research interest. Virtual reality has been used to investigate sleep deprivation effects in medicine [15, 43], particularly with surgeons. A virtual environment can safely and realistically simulate a surgical environment from which the impact of sleep deprivation can be measured. AR represents a logical step forward for medical imaging and in situ access to important patient data. Surgeons stand to benefit from having MRI visualizations available to them as overlays on the patient. Hansen et al. [21] employed projector-based AR to highlight liver tumors and their surrounding vessels to aid the performance of liver surgeons. Their findings showed that their sample of experts were all able to more quickly judge distances between the tumor and nearby risk structures.

3 Sleep Deprivation Study

We designed an experiment to explore the effects of SAR-based instruction on users' performance when sleep deprived. The objective was to capture the impact of sleep deprivation on task performance over the course of one night at multiple time points. In order to achieve this objective, we implemented a SAR-based procedural task, and tested participant performance at six time points, from 8pm to 8am. The procedure involved a button-pressing task on a dome-shaped apparatus with instructions for the press order provided either by projected annotations or on an adjacent monitor, depicted in Figure 1. The dome-shaped apparatus was chosen for its non-planar shape, differentiating it from a planar touchscreen. In addition, the simplicity of the design enabled rigorous, laboratory controls to be maintained. The apparatus has previously been shown to be sensitive to the instructional condition [29].

The hypotheses addressed in the experiment are as follows:

Hypothesis H1 SAR provides a sleep deprivation countermeasure for users performing a procedural task.

Hypothesis H2 Error increase rate over a night of sleep deprivation with SAR instructions will be less when compared to a traditional monitor display.

Hypothesis H3 Time performance deterioration rate over a night of sleep deprivation with SAR instructions will be less when compared to a traditional monitor display.

Hypothesis H4 Overall Psychomotor Vigilance Task performance will demonstrate negative effects of sleep deprivation on vigilance.

3.1 Experimental Design

A user study was conducted as a within-participants repeated measures design. The study compared performance on a procedural task, repeatedly measured over a night of total sleep deprivation. Two mediums of instructional display for the procedural task were compared: traditional monitor display and SAR display. In addition, sleepiness was measured before each testing point with the Psychomotor Vigilance Task (PVT-B) [11].

The study had approval from the University of South Australia Human Ethics Research Committee, using guidelines established by the National Health and Medical Research Council of Australia. Individuals were made aware that participation was completely voluntary and that they could withdraw at any time. All gave written consent to participate in the study.

3.2 Participants

Ten participants (three female) were recruited from students of the University of South Australia and the general public. A A$100 honorarium was provided to each participant for their time and inconvenience upon completion of the study, and the participants were provided a free taxi ride home once the experiment was completed. Potential participants attended a screening session where they were required to complete a general health survey and provide a urine sample for illicit drug screening. All participants tested negative for illicit drugs. Participants were only included for participation if between the ages of 21 and 40 years (M = 23.7, SD = 2.83) and had no history of sleep disorders. Participants completed a 10-minute training session, a shortened version of the experimental task. This was designed to limit learning effects on the study night.

During the preceding five days leading to the experiment the participants were required to perform a number of tasks to prepare them for the overnight experiment. The participants were asked to abstain from caffeine in all forms, alcohol and medication (participants requiring medication were excluded). The participants were required to wear a Philips Actiwatch 2 and keep a sleep journal for five nights prior to the study night to monitor their sleep routines. The mean time in bed was 8.28 hours (SD = 1.15), with the mean time asleep 6.83 hours (SD = 1.19).

3.3 Hardware Configuration

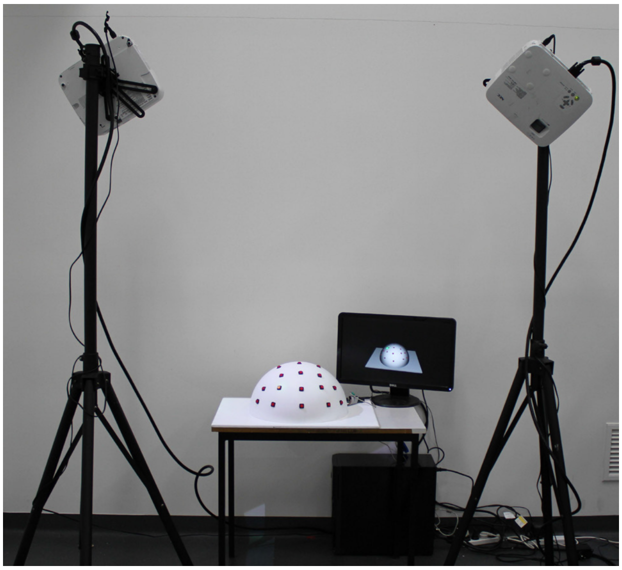


Fig. 2: Hardware setup of the experiment. Two projectors displayed annotations on the dome apparatus.

Two identical dome stations were configured (see Figure 2), and each station employed identical computer systems with the following specifications: Intel i7 processor, 16GB RAM, and an Nvidia Geforce GTX 770 graphics card. Two NEC NP510WG projectors with a resolution of 1280x800 and a brightness of 3000 Lumens were employed for each dome. Each station used a 22” LCD monitor with a resolution of 1920x1080 for the monitor based instructions (see Figure 1b). The button responses on domes were detected with an Olimex EasyWeb 3[1] MSP430-based microcontroller board. The Olimex EasyWeb 3 communicated button press and release events to the computer system over RS232 serial communication. Participants wore headphones to relay audio feedback from the system. These dome stations were placed in a separate room to support two participants at a time, and away from the other participants during the study. The headphones acoustically isolated the participants, and the dome stations were positioned outside the view of each of the participants.

[1]https://www.olimex.com/Products/MSP430/Starter/MSP430-EASYWEB-3

Table 1: All possible experimental condition combinations. The study had a $2*2*2$ experimental design.

Display Type	Presentation Type	Sequence Length
AR	ALL	12
AR	ALL	16
AR	SINGLE	12
AR	SINGLE	16
SCREEN	ALL	12
SCREEN	ALL	16
SCREEN	SINGLE	12
SCREEN	SINGLE	16

3.4 Procedure

Participants attended the CfSR for an overnight stay, from 8pm to 8am. Each overnight session had a maximum of four participants, facilitated by two researchers. Participants arrived at 8pm and were given a tour of the laboratory and introduced to each other. They had an hour to acclimate and settle into the surroundings before the testing schedule began. The overnight stay in the CfSR required the participants to remain awake for the duration. Throughout the study light intensity at angle of gaze was < 50 lux and ambient temperature was 22 ± 1°C (72 ± 1.8°F). Participants were not exposed to clocks or social time cues (e.g., internet, mobile phones, real-time television) and were unaware of the time; they surrendered watches and all electronic devices upon entrance to the laboratory. Snacks were provided to participants at 1200h and 0400h. The snacks were chosen to not contain stimulants, such as caffeine. During free time participants collected as a group in a lounge-like room in the sleep laboratory (see Figure 3). They could watch DVDs, play games (board/card), interact with the researchers and other participants, read, or listen to music. Participants were continuously monitored to ensure they did not sleep during the study.

Fig. 3: The lounge area where participants could relax when not testing.

The night was divided into testing sessions at six time points: 2100h, 2300h, 0100h, 0300h, 0500h and 0700h. At each testing block they first completed a three-minute PVT-B. The PVT-B requires participants to press a button on a hand-held device as soon as a visual stimulus is presented. Participants are instructed to react as quickly as possible. This measure is a well validated means of objectively measuring participant sleepiness. It is known to accurately map performance decline during total sleep deprivation [11]. This measure was included to provide a baseline to which the performance of the SAR test could be compared with the effects of sleep deprivation.

The experimental conditions consisted of 32 (2 sequence lengths x 2 presentation types x 2 display conditions x 4 repetitions) trials of button presses per session. The trials were randomly distributed, but comprised of eight possible combinations, as outlined in Table 1. The button sequence length was either 12 or 16 presses long. This was to examine whether longer, more complex sequences impact behavior in a different way to shorter sequences. The order of the buttons was random, but for hand travel consistency across trials and participants, sequence generation was run 100,000 times and the mean sequence length taken. All trials were then required to be within the mean and the mean length plus 5%. The presentation type also varied, with one option being all buttons annotated at once and the other being one button annotated at a time. This dichotomy was introduced to explore differences in task complexity. The main condition was the instructions being provided via projections directly on the dome apparatus (see Figure 1a) or shown as a 3D model on an adjacent monitor (see Figure 1b). The translation of instructions from one place to another resembled a common workflow in manufacturing where blueprint instructions must be followed on a working surface, or in the cab of a train where a driver may refer to a paper manual for advanced controls.

Participants were required to press buttons on the dome apparatus in numerical order, following the numbers presented with the annotations (see Figure 1). When the instructions were shown on the monitor the dome apparatus was blank, but the participants needed to translate the information shown into a correct button press. Likewise, when instructions were shown using SAR projections, the screen was blank. When displayed all at once, as shown in Figure 1a, participants were required to find and press buttons 1 through 12 or 16 (depending on the presented sequence length). When displayed singly, one annotation would appear and would disappear when correctly pressed. Participants were provided auditory feedback through the headphones; a different tone for correct and incorrect presses. Data were recorded for task completion time and errors made. The 32 trial task took approximately 15 minutes to complete.

At each testing time, participants completed the procedural task, as well as a small battery of cognitive tasks. These other tasks were for independent studies, and the results will not be reported here. The order of the procedural task and the cognitive battery was randomised. While two participants completed the procedural task, the remaining participants completed the battery. All testing was completed within the hour.

4 Statistical Analyses

The novelty of the study made prospective estimation of effect size for power analysis difficult. To put the sample size in context, effect sizes (partial eta squared, η_p^2) were medium to large for our primary dependent variable (response times on the AUR) for condition ($\eta_p^2 = 0.78 - 0.89$), time ($\eta_p^2 = 0.24 - 0.50$) and condition∗time ($\eta_p^2 = 0.09 - 0.24$). With a correlation among repeated measurements of 0.53 (and $\varepsilon = 1$), at the smallest effect size $\eta_p^2 = 0.09$, for the condition∗time interaction, we would require 12 participants to be sufficiently powered $1 - \beta = 0.80, \alpha = 0.05$. However, it should be noted that this is a conservative estimate, since this traditional type of power analysis recognises a single within-subjects factor (time). That is, while in the current study, all participants completed all forms of the task at all six time points across the night, in the power calculations, the condition effect is assumed to be independent. With these considerations in mind, particularly given the repeated measures design, study power was considered to be sufficient. As a relative comparison, similar studies investigating the effects of a single night of total [12, 22] and even partial [9] sleep deprivation with repeated measurement have included sample sizes of nine or ten.

4.1 Procedural Task

From the procedural tasks, mean response times per button press and total number of errors were computed across each block of four trials for each display condition (spatial augmented reality (AUR)/traditional monitor (SCREEN)), presentation type (ALL/SINGLE) and each task length (12/16 buttons).

In order to examine differences in response times between conditions and presentation types across time, a Mixed Effects Analysis of Variance was conducted. For each task length, models specified fixed effects of condition, presentation type and time, and all interaction effects, with a random effect of subject on the intercept. To further investigate significant condition∗time interaction effects, planned contrasts were conducted, within each condition, with points 1-5 compared to the last testing point.

In order to examine differences in number of errors between conditions and presentation types across time, Generalized Estimating Equations were used, which are an appropriate technique for analyzing repeated measures data where the dependent variable is a count. The model specified a Poisson distribution with a log link function and an exchangeable working correlation matrix structure [2], with error count as the dependent variable, a single factor of time, and subject ID as a panel variable across time. Due to the low number of errors, particularly in the AUR condition, to avoid minimum cell size issues, rather than running models with higher order interaction terms, models were run separately for each presentation type (ALL/SINGLE). For the 12-button task, there were almost no errors in the AUR condition. As such, separate models were run, one for each presentation type, with error count as a dependent variable, a single factor of time, and subject ID as a panel variable across time. For the 16-button tasks, models specified a dependent variable of error count, factors of condition, time and their interaction, and subject ID as a panel variable across condition and time. Consistent with all other models, to further investigate significant effects, planned contrasts were conducted, with points 1-5 compared to the last testing point.

4.2 Three-minute Psychomotor Vigilance Task (PVT-B)

From the PVT-B tasks completed following each procedural task, two metrics were calculated: mean response times per trial (MeanRT) and total number of errors, which included false starts (pressing the response button in the absence of a stimulus) and incorrect button presses.

In order to examine differences in MeanRT over time, Mixed Effects Analysis of Variance was conducted. This analysis is an extension of the general linear model (more traditional analysis of variance), which appropriately distinguishes within and between subject variance [47]. The model specified MeanRT as the dependent variable, with a fixed effect of time (2100h, 2300h, 0100h, 0300h, 0500h, 0700h) and a random effect of subject ID on the intercept. This random effect allows each subject to have their own intercept, or starting point [47]. To further investigate differences across time, to avoid multiple comparisons resulting in an elevated risk of Type 1 Error, or the potential requirement for corrections for multiple comparisons [34, 41] planned contrasts were conducted, with points 1-5 compared to the last testing point.

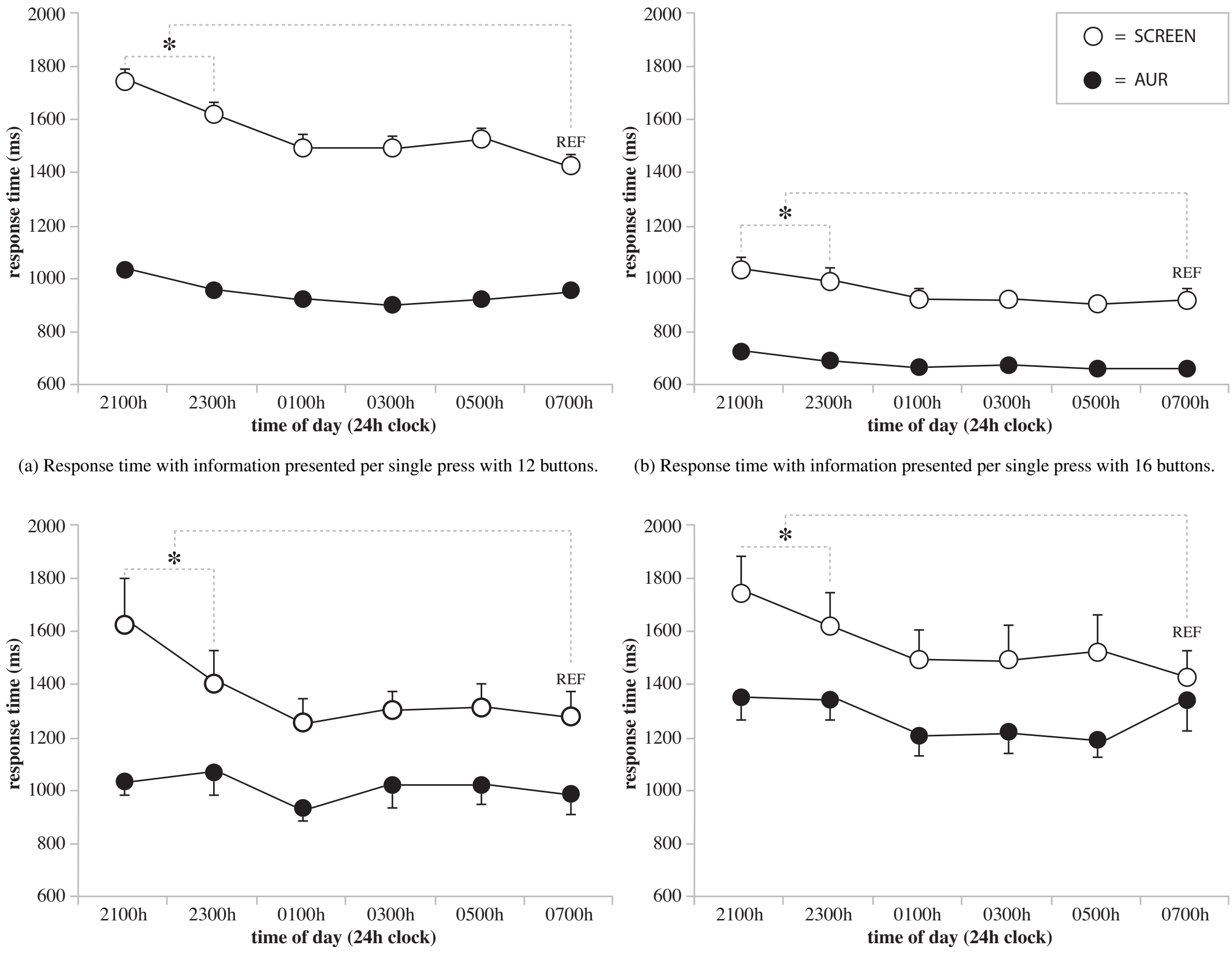
In order to examine differences in number of errors over time, Generalised Estimating Equations (Poisson distribution with log link and exchangeable covariance structure, as above) for count data were used. As described above, planned contrasts were conducted, with points 1-5 compared to the last testing point.

5 Results

The results for the procedural task response time will be presented first. These results will be followed with a description of the results for the procedural task response error. Finally, the three-minute PVT-B results will be presented.

5.1 Procedural Task Response Times

For the 12-button task, there were significant main effects of condition, presentation and time ($p < 0.05$, Table 2). There was a significant



(a) Response time with information presented per single press with 12 buttons.

(b) Response time with information presented per single press with 16 buttons.

(c) Response time with information presented all at once with 12 buttons.

(d) Response time with information presented all at once with 16 buttons.

Fig. 4: Mean and standard error (whiskers) response time per button press in milliseconds (msec). Results of planned contrasts across time are displayed in grey, with each time point compared to the final test at 0700h (*REF*), ($^*p < 0.05$).

condition∗presentation interaction effect ($p < 0.05$, Table 2), such that response times were longer in the SCREEN condition than the AUR condition, and the difference between conditions was larger for single presentation, compared to all together (Figures 4a and 4c). There was also a significant condition∗time interaction, such that over the sleep loss period, response times became faster in the SCREEN condition, but remained relatively stable in the AUR condition (Figures 4a and 4c); summarised in Figure 7a). Planned contrasts revealed that in the SCREEN condition, response times at the first two time points (2100h, 2300h) were significantly longer than during the final time points (0700h; $p < 0.05$). For the AUR condition, there were no significant differences across time points (Figures 4a and 4c).

For the 16-button task, there were significant main effects of condition, presentation and time ($p < 0.001$), and no significant interactions (Table 2). Response times were higher for SCREEN compared to AUR conditions, and for presentation of information all together, compared to single presentations with each button press. Post-hoc contrasts indicated that response times during the first two time points (2100h, 2300h) were significantly longer than during the final time point (0700h; $p < 0.05$, Figures 4b and 4d).

5.2 Procedural Task Errors

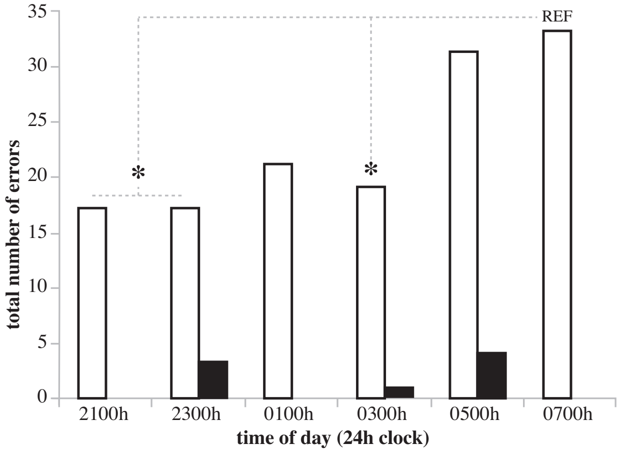
For the 12-button task, there was no significant difference in number of errors across time in the SCREEN condition when all information was presented together. However, there was a significant difference in errors across time in the single presentation type ($p < 0.001$), with planned contrasts indicating that tests at 2100h, 2300h and 0300h had significantly fewer errors than the last test at 0700h (Table 3), Figure5a).

For the 16-button task, when the information was presented all together, there were significant main effects of condition and time ($p < 0.05$; Table 3). There was also a significant condition∗time interaction ($p < 0.05$) such that over the sleep loss period, errors increased in the SCREEN condition, but remained relatively stable in the AUR condition (Figure 5d; summarised in Figure 7b). Planned contrasts revealed that in the SCREEN condition, tests at 2300h and 0300h had significantly fewer errors than the test at 0700h ($p < 0.05$). There were no significant differences across time in the AUR condition, which overall, was associated with fewer errors than the SCREEN condition.

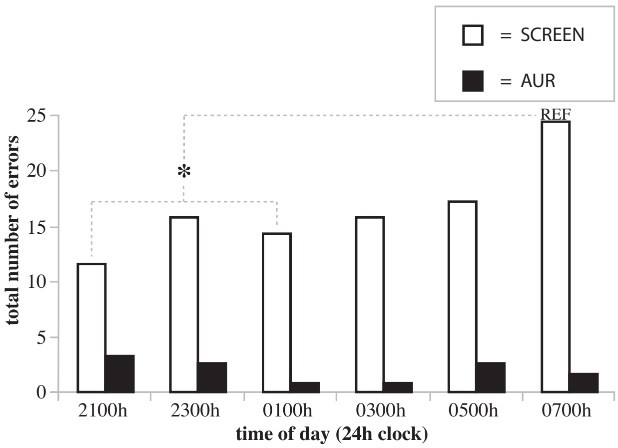
When the information was presented singly for each button press, there was a significant main effect of condition, and a significant condition∗time interaction ($p < 0.001$), such that errors increased in the SCREEN condition, but remained stable in the AUR condition (Figure 5b; summarised in Figure 7b. Planned contrasts revealed that in the SCREEN condition, tests at 2100h, 2300h and 0100h had significantly fewer errors than the test at 0700h. There were no significant differences across time in the AUR condition, which overall, was associated with fewer errors than the SCREEN condition (Table 3, Figure 5b).

5.3 Three-minute Psychomotor Vigilance Task (PVT-B)

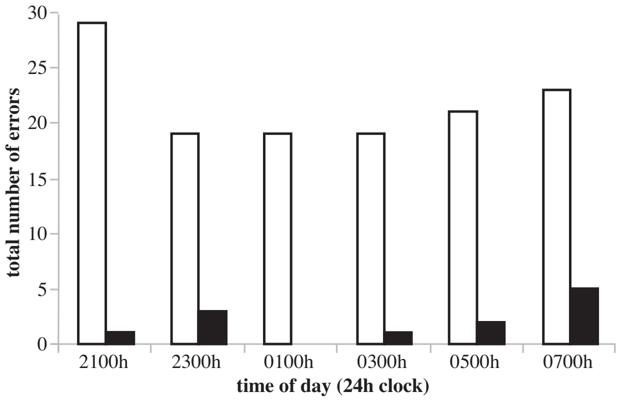
Over the sleep loss period, PVT-B response times became longer and errors were more frequent, demonstrating increasing impairment across the night (Figures 6a and 6b). There was a significant main ef-



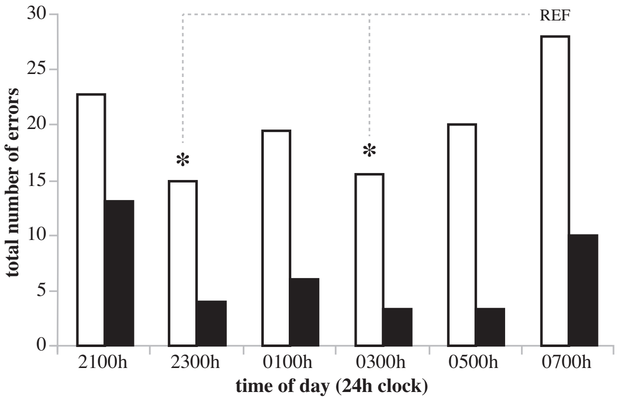
(a) Total errors with information presented per single press with 12 buttons.



(b) Total errors with information presented per single press with 16 buttons.



(c) Total errors with information presented all at once with 12 buttons.



(d) Total errors with information presented all at once with 16 buttons.

Fig. 5: Total number of errors. Results of planned contrasts across time are displayed in grey, with each time point compared to the final test at 0700h (REF), ($p < 0.05$).

fect of time ($F_{5,45} = 3.254, p < 0.05$) on mean response times, with planned contrasts indicating that they were significantly longer at 0700h compared to 2100h, 2300h and 0100h. There was also a significant main effect of time for errors ($X_5^2 = 55.204, p < 0.001$), with planned contrasts indicating that there were significantly more errors during the final trial at 0700h, than during any other trial ($p < 0.05$).

6 Discussion

This study has shown AR to exhibit a protective effect against procedural task performance decline while sleep deprived. We draw this conclusion looking at the interaction effects of the AUR condition that illustrated no significant change in response time or errors for participants while sleep deprived at all time points. This result supports Hypothesis H1 as the AUR condition did not suffer from the detrimental effects of sleep deprivation on task performance while the SCREEN condition demonstrated a significant increase in errors.

The AUR condition consistently enabled faster response times and fewer errors than with the SCREEN condition, with no exceptions. Analysis of the SCREEN response times did show a significant performance increase across both presentation types and sequence lengths, but this clearly came at the expense of significantly increased errors, in all cases excluding ALL with length 12.

Overall, the study has shown that the SCREEN condition was sensitive to sleep deprivation resulting in an increase of errors over the night. The SCREEN condition required participants to translate the position of the target button(s) from the monitor to the dome apparatus. This is a cognitive task, likely relying upon aspects of executive functioning known to be negatively affected by sleep deprivation. Importantly, we have shown that compared to the SCREEN condition, SAR instruction led to reduced errors and time and was not sensitive to the effects of sleep deprivation. SAR can, therefore, be offered as a novel and exciting countermeasure for sleep deprivation, especially for procedural tasks requiring continuous vigilance and accurate performance.

As expected, the number of errors made in the SCREEN condition showed a general increase as the study night progressed. In each condition, except ALL with length 12, two or more earlier time points exhibited significantly fewer errors when compared to the final time point. The error interaction effect between condition and time, as shown in Figure 7b, illustrates a trend toward increased errors across all conditions. As such, hypothesis H2 was supported. Conversely, the AR presentation condition showed no significant change in errors. Relatively few were made in comparison to the SCREEN condition and this was particularly the case in the SINGLE presentation condition.

Contrary to predictions, time performance in the SCREEN condition did not deteriorate over the study night. In fact, when the first two time points are compared to the final, there is a significant improvement in response time. As such, hypothesis H3 was not supported. Figure 4 does show that only time points 2100h and 2300h were significantly slower than the final time point at 0700h. This suggests that an initial learning effect was evident in the first two points, and then performance plateaued. Despite this finding, there is an interesting interaction taking place that is corroborated by an entire field of research, namely, the speed-accuracy tradeoff.

The tradeoff that occurs between favoring either speed or accuracy

Table 2: Mixed Effects Analysis of Variance for procedural task response times.

	12 buttons			16 buttons		
	df	F	p	df	F	p
c	1,230	238.6	<0.001	1,230	146.7	<0.001
p	1,230	336.3	<0.001	1,230	707.2	<0.001
t	5,230	5.0	<0.001	5,230	4.7	<0.001
$c*p$	1,230	5.0	<0.001	1,230	0.0	0.891
$c*t$	5,230	2.3	0.048	5,230	1.1	0.345
$t*p$	5,230	1.2	0.276	5,230	0.7	0.620
$c*p*t$	5,230	1.0	0.415	5,230	0.8	0.566

Effects of condition (c) (AUR/SCREEN), presentation type (p) (ALL/SINGLE) and test time (t) (2100h / 2300h / 0100h / 0300h / 0500h / 0700h) on the average response time per button press for 12-button (left) and 16-button tests (right). All main and interaction effects are shown, with degrees of freedom (df), F-ratio for each effect (F) and related significance (p-value).

Table 3: Generalised Estimating Equations for procedural task errors.

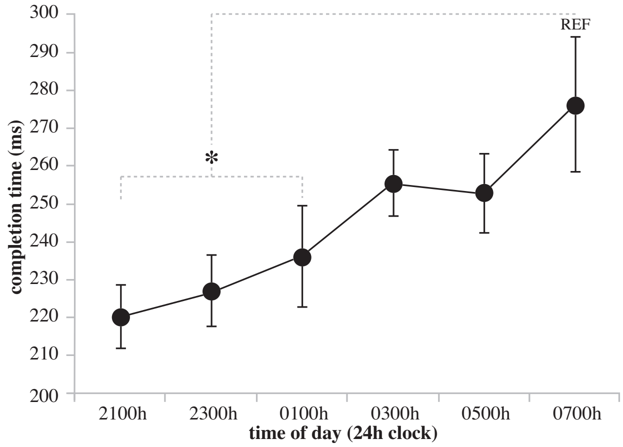
	12 buttons			16 buttons		
	df	χ^2	p	df	χ^2	p
ALL						
c	-	-	-	1	12.4	<0.001
t	5	3.4	0.637	5	37.4	<0.001
$c*t$	-	-	-	5	13.4	0.020
SINGLE						
c	-	-	-	1	119.4	<0.001
t	5	38.3	0.001	5	3.8	0.572
$c*t$	-	-	-	5	21.4	0.001

Effects of condition (c) (AUR/SCREEN) and test time (t) (2100h / 2300h / 0100h / 0300h / 0500h / 0700h) on the total number of errors for 12-button (left) and 16-button tests (right). Models are shown for each presentation type (ALL/SINGLE) separately. Due to the very low number of errors in the AUR condition for the 12-button tasks, models tested the effect of time in the SCREEN condition only. All main and relevant interaction effects are shown, with degrees of freedom (df), chi-square testing each effect in the model (χ^2) and related significance (p-value).

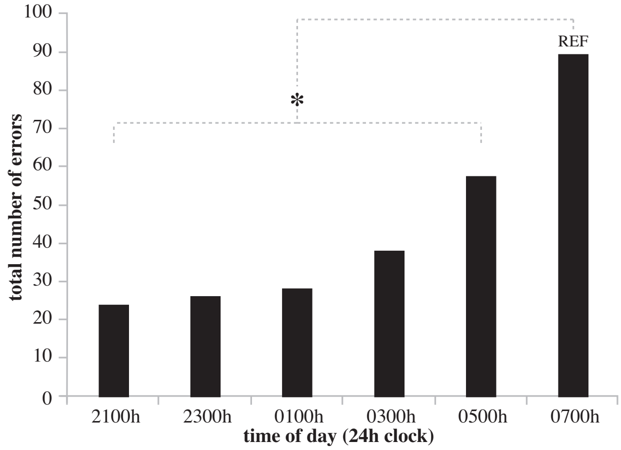
is a well researched phenomenon [51]. It states that by biasing one aspect of a task, the other will suffer. This is observable in the present study. The participants were told to complete the task as quickly and accurately as possible. The continual improvement of response time in the SCREEN condition highlights that participants generally chose to sacrifice being accurate in order to maintain their speed. This phenomenon did not occur in the AUR condition where performance across both response time and errors was consistent.

Incorporating the PVT-B into the research design enabled a reliable comparator for the effects of sleep deprivation. The PVT-B has been validated to be sensitive to sleepiness and the results shown in Figures 6a and 6b demonstrate degradation of response time performance and an increase in errors made. This supports hypothesis H4. When the PVT-B response time is compared to the main task response time (see Figure 7), an inverse slope is seen. This is particularly evident for the SCREEN condition. It is clear that despite the participants experiencing negative effects of sleep deprivation, as evidenced by the PVT-B results, their response times on the procedural task remained constant over the night. Figures 7a and 7b shows, in the SCREEN condition, that as the response time decreased the errors increased.

There are a number of parameters that need to be further explored



(a) PVT-B: Mean and standard error response time per trial in milliseconds. Results of planned contrasts across time are displayed in grey (REF), $^*p < 0.05$.



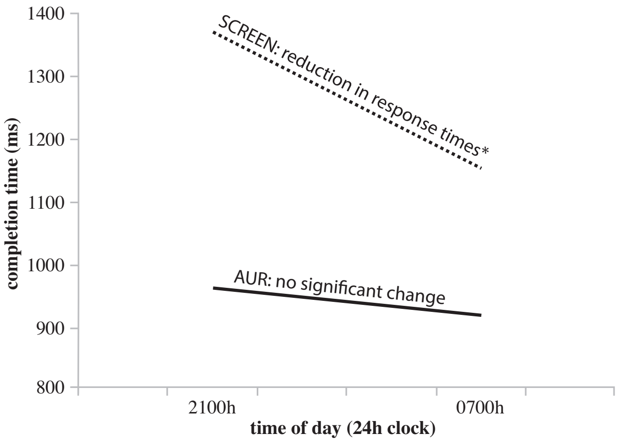
(b) PVT-B: Total number of errors. Results of planned contrasts across time are displayed in grey (REF), $^*p < 0.05$.

Fig. 6: PVT-B: Response times and total errors.

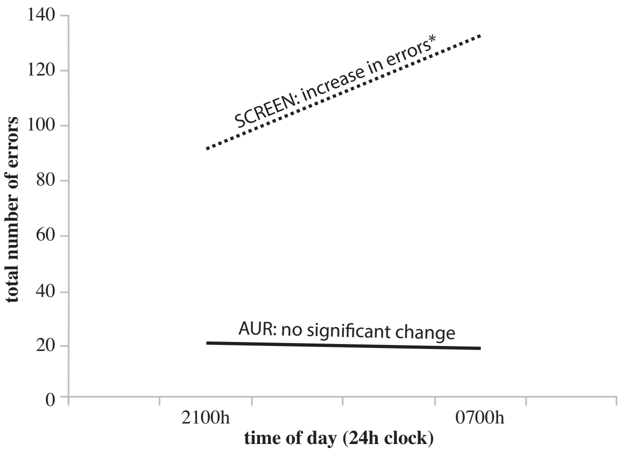
to better understand how our new countermeasure can be applied to industry applications. The environment was set up with laboratory conditions to simplify the task. This incorporated strict noise, lighting and temperature control. Using the SAR projection technology in situ with specific industry environmental parameters may influence the outcome. The tasks performed by operators are also likely to be more complicated and contain decision-making components that demand closer attention. The dome-shaped button apparatus was painted white and optimized for ideal viewing of projections. Surfaces in industry settings may not be as suitable for SAR-based techniques so future work could explore projecting on more complex surfaces.

It is important to acknowledge the potential for floor (or basement) effects to have impacted study results. It is possible that response time plateaus during the second half of the night may represent the test floor —the point at which the task is no longer sufficiently sensitive to show differences. Given that the AUR condition results in scores that are both faster and more accurate, it could be argued that the AUR renders the task simpler and lowers the floor for performance on this task. It would be interesting to explore the AUR technique with tasks of differing sensitivity under conditions of sleep deprivation.

Furthermore, the participants were only sleep deprived of one night's sleep. Future research could investigate how SAR impacts performance when applied to users with partial sleep deprivation; shift workers, for example. Lastly, in regard to the applicability of these findings to AR in general, an optical or video see-through HMD or



(a) Summary figure for the condition∗time interactions for average response times.



(b) Summary figures for the condition∗time interactions for total number of errors.

Fig. 7: Procedural Task Condition∗Time Interactions. Data are shown for the first time point (2100h) compared to the last time point (0700h), collapsed across presentation type (ALL/SINGLE) and number of buttons (12/16). *indicates a significant change at $p<0.05$.

mobile device could afford much the same removal of the negative effect of spatial information translation imposed by the SCREEN condition. Further research could explore whether similar performance protection is exhibited by participants using alternate forms of AR.

SAR may help sleep deprived users in a number of ways, not only for procedural task guidance. Without requiring any conscious attention to information presented outside the field of view, SAR could present reminders or alerts to a sleep deprived viewer. Similarly, a SAR-based system could maintain a list of tasks to perform and issue guidance on their completion. Complex instructions, including video, could be projected onto the viewing surface. These concepts require additional research, but are areas in which we envision SAR providing benefit in sleep research.

7 Conclusion

This paper presents an inaugural collaboration between the fields of AR and sleep research. The results offer AR display techniques as a new alternative to existing countermeasures for mitigating the negative effects of sleep deprivation. This was achieved by examining two instruction conditions, namely AUR and SCREEN. The AUR condition was shown to maintain performance throughout a night of total sleep deprivation, from both a response time and error perspective. Conversely, the SCREEN condition suffered from a speed-accuracy tradeoff. In some of the common AR application domains, this type of strategy for coping with sleep deprivation would be unacceptable; a surgeon or train driver cannot make increasing numbers of errors throughout a shift.

We believe that our straightforward design and procedural task lends our findings generalizability to many industry applications for AR. Occupations that require a continual completion of sequential tasks could benefit from AR-based guidance. We envisage shift workers performing repetitive tasks at a control panel, for example, being shown projected annotations to avoid fatigue-based errors. Used correctly, AR could significantly decrease human error when workers are required to perform while sleep deprived.

Overall, our findings have shown for the first time that AR techniques can be employed to promote performance stability in sleep deprived circumstances. Further investigations may incorporate a complex task more representative of a specific role in a workplace. This could follow a similar design to the present study, or mimic shift worker schedules. Based on the success of this first examination, we foresee it being possible to apply AR techniques as a sleep deprivation countermeasure in a number of application domains.

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