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Assessing Human Performance and Fatigue in a Control Room during ISS Operations

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This study aimed at exploring how human centered sensing can be used to assess performance and fatigue in a control room setting. The study was performed at CIRiS' (Centre for Interdisciplinary Research in Space) control center while the staff was monitoring an experiment onboard the International Space Station (ISS). We had two parallel objectives: 1) to explore the participants' use of the display screens in the new control center set-up; and 2) to identify eye-tracker markers that can signal fatigue during shift work. Six participants took part in the study, wearing eye-tracking glasses with a positioning tracking device for selected 30 minutes periods at the beginning and end of the shifts; as well as answering to fatigue and cognitive performance tasks at the beginning and end of each shift. A digit memory span task did not seem to be sensitive to the beginning/end of shift variable. Self-reported fatigue scales showed a tendency for lower scores in the beginning of the shift when compared to its end. The data from the eye-tracking analysis revealed a differential use of the control interfaces in the station at the beginning and end of shift. Regarding the fatigue levels, the eye-tracking indicators were not sensitive to any differences in the beginning/end of shift.

I. Introduction

THE current study was conducted with two core objectives: the first was to provide a preliminary assessment of the adequacy of the new control room facilities at CIRiS – Centre for Interdisciplinary Research in Space, exploring how the researchers were using the new set up in an ongoing experiment; and a second objective was to use this opportunity as a pilot test for the use of the Synopticon system in field data collections. This system enables eye-tracking and position tracking of participants, providing live feedback of heat maps and areas of interest.

The CIRiS control room has been an operational part of the International Space Station (ISS) ground infrastructure since 2006, and has since supported several diverse experiments within the fields of plant biology; education objective activities; and technology demonstrators. The control room has also been utilized for simulations, training of control room operators, and for controlling and monitoring ground tests of space experiments. Additionally, the control room has been used for outreach purposes including visits from school and university students and media.

The available rooms in the cellar of a university building did not accommodate these diverse activities sufficiently. The work environment (light, air, ergonomic design of work stations) was poor, it was not possible to perform several activities in parallel and the possibility for R&D and outreach activities were limited. The need for a new control centre with the desired functions was recognized and CIRiS designed and built a new CIRiS Control Centre that officially opened in May 2017. The standard ISO 11064 "Ergonomic design of control centres" was used as a guideline for the design process.

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The current study was conducted at one of the two consoles in the control room, dedicated to remote monitoring and control of the European Modular Cultivation System (EMCS) which is installed onboard the ISS. The EMCS is owned by The European Space Agency (ESA) and is basically a small greenhouse where plant experiments in microgravity are performed. The planning and preparation phase for each experiment can last for several years and there has been approximately one experiment conducted in the EMCS per year. During execution the control room operators man the console 24/7 in three shifts for each 24-hour period over 2-3 weeks. The console operators interpret and respond to telemetry from the EMCS regarding experiment parameters (plant access to water, light, temperature) and the technical status of the payload. They assist the astronauts when they performed EMCS activities, all in close cooperation with the NASA Payload Operations and Integration Centre (POIC) control room in Huntsville. The main communication and coordination tool is the voice loop system that allows direct communication with personnel in other mission control rooms as well as the possibility for monitoring activities of other controllers and mission events on ground or on ISS without disrupting their own activities or activities of others (Patterson 1999). The operators also have contact with scientists and engineering support, either on site or by phone/e-mail as well as utilizing other technical operations tools, like the ISS timeline or information exchange and reporting systems. In addition they follow generic and specific procedures and produce documentation and reports (Johansen 2016). The operators have all followed an internal training and simulation program and are certified before being allowed to work in the control room.

The new EMCS console was placed in a larger room than before, with upgraded ventilation, adjustable desks, chairs and lighting to improve the overall working conditions. However, the software for EMCS was developed more than 15 years ago and was not available for update; hence the displays presenting information from the EMCS could not be improved. To mitigate the not optimized screen displays the arrangement of screens were altered. The old console had one row of small screens with three large screens directly above, all showing parts of primary information needed for operations. The new setup was based on task analysis, mock-up walk-throughs and interviews with all console operators. The idea was to group displays according to their use and type of information, e.g. the most frequently used displays or those associated with high priority information were group together.

Figure 1 shows the set-up of the workstation at the new control center. Screen 1 shows the voice loop system; screen 2 presents TReK, a system connection to NASA that enables reception of telemetry and sending of telecommands; screen 3 shows the main EMCS displays with information on the hardware and experiment status; screen 4 primarily shows the console log where all events are continually logged or other documents like procedures/daily reports; screen 5 usually shows the OPTIMIS system, a timeline in use by all ISS control centres and astronauts showing all planned activities on the ISS; screen 6 is used as a multipurpose desktop showing applicable spreadsheets, presentation slides, and other documents selected by the operator; screen 7 shows a live video feed from ISS; and finally screen 8 shows ESA operational tools (e.g. CEFN – console electronic flight note system – information exchange / approval of products/activities on flight director level).

Figure 1: Workstation at CIRiS's control center.

On initial informal interviews with the staff, one of the most common complaints regarding the old control room was related to feelings of fatigue and exhaustion when they were in operation. As such, in this assessment of the new control room we tried to evaluate differences in self-reported fatigue in the beginning and end of shift. Likewise, considering that the staff reported feeling excessive tiredness accompanied by some other symptoms like headaches and difficulties in concentrating in the old control room, we included a cognitive performance level to assess whether these complaints were solved in the new control room set-up.

There is a vast literature on the impact of shift work on cognitive performance (e.g. Kazemi, Haidarimoghadam, Motamedzadeh, Golmohamadi, Soltanian, & Zoghipaydar, 2016), fatigue (e.g. Åkerstedt, & Wright, 2009), and sleep patterns (e.g. Rouch, Wild, Ansieu, & Marquié, 2005) that has been consulted to prepare this study. Nonetheless, there are relevant specificities in the current study that make the context of the work environment not directly comparable with the traditional shiftwork focus: the staff at CIRiS works only temporarily in shifts (for the duration of the experiments at ISS) and for a short time period (about 2 weeks in rotation shifts between 6 staff elements).

II. Method

A. Participants

All members of CIRiS staff participated in the study: six participants, two male. The average age of the participants was 42.2 years old (*SD*= 4.8).

B. Equipment

Eye and Positioning Tracking

SynOpticon is a real-time sensor fusion platform that receives streams from different sensors and combines data features. The main purpose of SynOpticon for this study was to automatically detect which screens the participants were looking at by fusing position tracking and eye tracking data. Using eye tracking out of the box will normally provide a video stream that has the users' gaze location overlaid. This requires manual encoding of the gaze data in order to know what object the user is looking at. This is typically a long and cumbersome process that highly expands the time required for data analysis. SynOpticon allows this process to be automated and performed in real-time. As such, beyond saving significant time in the data analysis, it enables an immediate feedback of the user's behaviour by showing heat maps in real time.

A modelling tool was created by attaching position tracked markers to a rod with a tip; the tool was calibrated in SynOpticon so that the location of the tip of the tool is known in the virtual world. By positioning the tip of the tool on the surface of the objects, and recording its locations as areas of interest (AOI), a mapping of the objects of interest is obtained. SynOpticon contains algorithms that simplify the creation of shapes such as planes, curves and splines, reducing the amount of measurements required to create the 3D objects. For instance, to model a plane you only have to take three measurements at the corners of the plane.

By fusing position tracking and eye tracking data it is possible to project the users gaze into the virtual model to detect when the users gaze is interacting with the AOIs. SynOpticon registers how many times AOIs are looked at and for how long they are looked at. The data can be exported for further analysis.

- System hardware

4x Optitrack position tracking camera, 2x Prime 13 and 2x Prime 13W (240Hz)
1x SMI eye tracking glasses 2 (120Hz)

- Position tracking cameras setup

Two tripods positioned on both sides of the tracking area. Each tripod was mounted with both Prime 13 and Prime 13W cameras. The tracking area was only 2.5m x 1m x 1.5m as such 4 cameras were enough to cover the area. The cameras were calibrated before the first session and then calibrated as necessary as the lighting changed during the day/night cycle.

- Eye tracking glasses (ETG)

The ETG were used together with the SMI mobile phone units. Reflective markers were attached to the glasses in order to track its position in the virtual model. The ETG was calibrated using a 3point calibration on a screen located in front of the participant. Top left, top right and the middle of the bottom screen was used as the calibration points.

- SynOpticon

First the 3D model of the AOIs was created, see Figure 2. To allow the participants to adjust the height of the table without invalidating the 3D model the table was positon tracked. The modelled screens were then parented to the table so that they would move with the table in the virtual model.

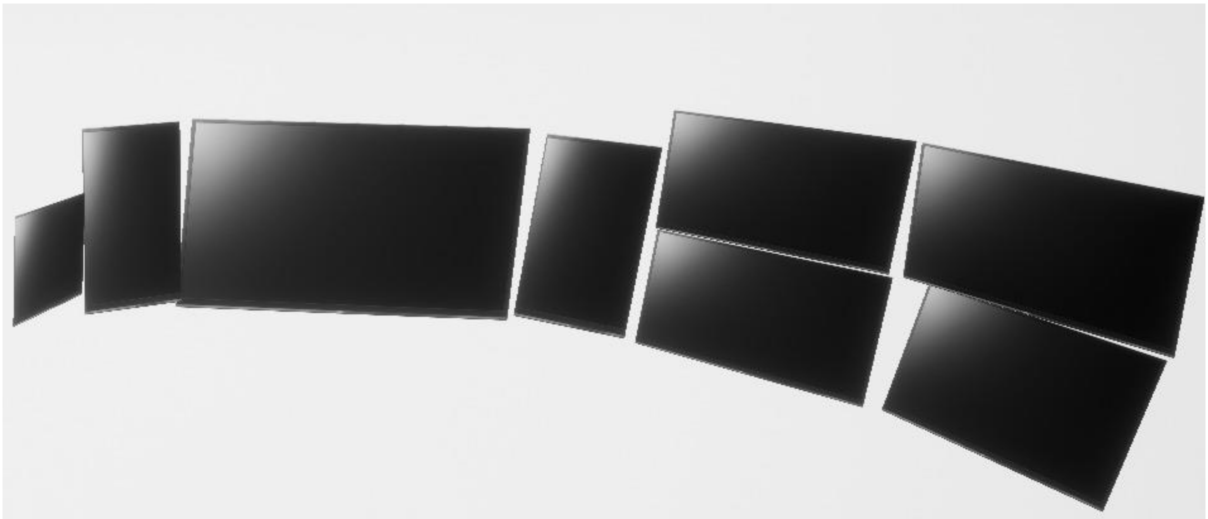

Figure 2: The virtual model of the screens.

Fatigue Scales

Versions of the Chadler Fatigue Scales (Chadler, Berelowitz, Pawlikawska, Watts, Wessely, Wright, & Wallace, 1993) for cognitive and physical fatigue were used in the study. These scales were developed within clinical settings but have been successfully used to measure fatigue not only with patients but also in the general community (Cella & Chalder, 2010). The physical fatigue scale has 8 items and the cognitive fatigue scale has 7 items. Table 1 shows the exact items presented in each scale. At the beginning of the shift the participants had to rate their agreement to each item on a lickert scale from *1 – Not at all* to *5 – A great deal*. At the end of the shift, the same scale was presented, but the participants were asked to assess the change in their own state in comparison with the beginning of the shift in a lickert scale from *1 – Much less* to *5 – Much more*, where 3 represented *No change*.

Table 1 List of items in each fatigue scale

Physical Fatigue Scale		**Cognitive Fatigue Scale**	
1	Are you having problems with tiredness?	1	Do you currently have problems concentrating?
2	Do you feel like you need to take a rest right now?	2	Are you feeling less motivated than usual?
3	Do you currently feel sleepy or drowsy?	3	Are you having problems thinking clearly?
4	Do you currently have problems starting activities?	4	Are you having difficulty thinking of the right words to use?
5	Would you experience more weakness than usual if you started an activity now?	5	Is your attention span less than usual right now
6	Are you currently lacking energy?	6	Are you feeling prone to slips of the tongue?
7	Do your muscles feel tired right now?	7	Is your memory capacity currently less than usual?
8	Do you currently feel weak?		

Cognitive Performance Task

A digit span task was used as for cognitive performance assessment. We used the task developed by Cognitive Tools (von Bastian, Locher, & Ruflin, 2013; Stone & Towse, 2015) – this is a short-term memory task that required the recall of digits in the accurate serial position. The participants saw in the computer screen sequences of digits, varying between 10 and 99 and presented in lists with 2 to 9 items in a crescent order. The participants had to recall each item in the list in the correct order after the list presentation. They were prompted to input the items one by one. Digit span tasks are working memory tasks that require the storage and recovery of information over a brief interval, and it entails recalling two types of information: what the items are and the correct order they were presented (Baddeley, Eysenck, & Anderson, 2009).

Survey on the expected use of the displays

All of the participants in the study were asked to fill in a quick survey on the expected use of the displays in the new control room and we obtain responses from 5 participants. The survey had 6 questions. Three of the questions were lickert scale questions, 1 was a Yes/No question and the two final questions were open. Table 2 has a description of each of the presented questions.

Table 2 Questions in the online survey

Question	**List of items**	**Type of response**
Please indicate how you expect each screen to be used in the beginning of the shift	Screen identification (11 screens)	Lickert scale. 1 – Least used/Looked at *to* 7 – Most used/looked at
Please indicate how you expect each screen to be used in the end of the shift	Screen identification (11 screens)	Lickert scale. 1 – Least used/Looked at *to* 7 – Most used/looked at
Please classify each of the following shift tasks according to their expected frequency	List of 12 tasks: registering events in shift (writing), monitoring video feed, controlling voice communication, reading log of previous events, following procedures (reading), use of personal computer for experiment work, use of personal computer for other work, monitoring data overview information, monitoring the experiment timeline, checking ESA tools, checking NASA connection, monitoring specific EMCS data	Lickert scale. 1 – Never *to* 6 – Very Frequently, plus a Not sure option
Do you anticipate differences in the tasks in the beginning and end of shift?	Yes/No	Single choice.
Which types of tasks are expected in the beginning of the shift? Please provide examples.	Text entry	Open answer
Which types of tasks are expected in the end of the shift? Please provide examples.	Text entry	Open answer

C. Procedure

The data collection was done in two consecutives weeks while the CIRiS experiment was taking place. We collected data through two days in each week, covering a total of 4-5 of 6 shifts. The study procedure involved four different phases:

- Pre-shift self-rating scales and memory task

- On-shift eye tracking and position tracking data
- Post-shift self-rating scales and memory task
- Participant estimation of time spend on each control room display in the beginning *versus* end of shift

In the beginning of the study the participants were informed about its goals and were provided with a general description of the tasks. Then, they were invited to read and sign an informed consent form. After this, the participants were taken to a desk with a computer where the memory task was presented with duration of between 5 and 10 minutes. The next task was filling in two self-rating fatigue scales: one on cognitive fatigue and one on mental fatigue (each scale took less than 5 minutes to complete).

Afterwards, the participant entered the control room where the eye-tracking and positioning tracking devices were calibrated by the researchers – calibration was typically under 10 minutes, but it took more time (up to 20 minutes) in some instances. After calibration the participant was asked to proceed as usual and 30 minutes of eye-tracking data were collected within the first hour of shift work. Here the participants could take off the eye-tracker and resume to normal activities. At the end of the shift, during the last hour another 30 minutes of eye-tracking data were collected, with the participants needing to wear the glasses again and recalibrate the equipment.

At the end of the shift, the participants repeated the same memory task to assess cognitive performance and were asked to fulfill the fatigue tasks by comparing how they felt in relation to the beginning of the shift measurement.

The researchers took note of the time of day each start and end of shift took place in.

Before being presented with the findings from the studies, the participants were also invited to an online survey where they were asked to rate how often they expected each of the control room displays was used in the beginning *versus* the end of the shift. This information was taken into account when analysis the actual time they spend looking at each screen during the data collection.

III. Results and Discussion

A. Intended *vs* Real use of the interface

Only one of the five survey respondents reported that a difference between the tasks in the beginning/end of shift was not expected. The largest differences were expected in the use of the EMCS overview displays (screen 3), the TreK (screen 2) and the voice loop (screen 1) displays, with the first being more used in the beginning of the shift and the other two at the end of the shift.

Figure 3 shows a weighted score for the expected use of each screen, showing only the screens that were considered relevant by the staff. The score is obtained by multiplying how often each screen was expected to be used by the staff (on a scale of 1: *least used/looked at* to 7: *most used/looked at*) by the number of staff members that chose that rating – as such the maximum score would be the 5 participants rating a screen as used very often (score of 35) and the lowest score would be none of the participants rating a screen as being used (score of 0).

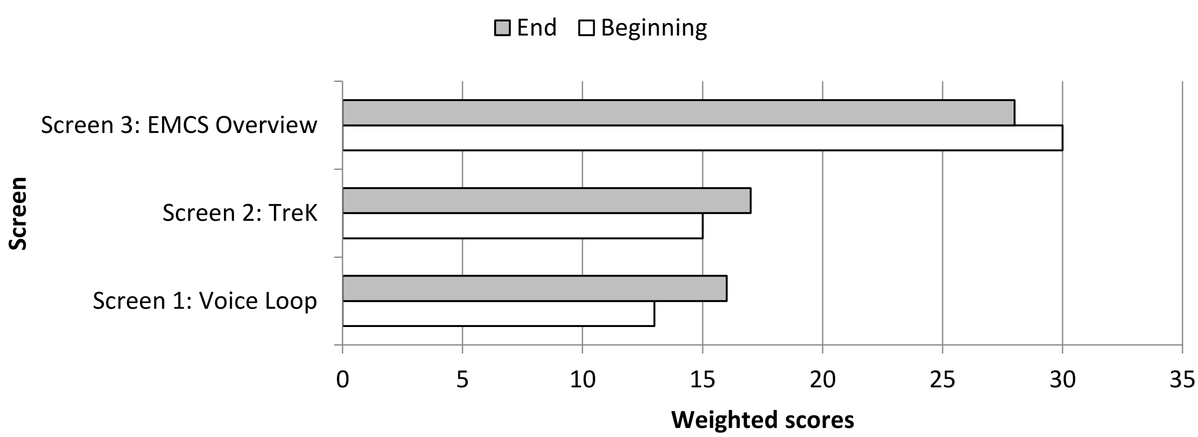

Figure 3: Expected differences in the use of the screens as reported by staff

The eye-tracking data are shown in figure 4 below. The data show that screens 1 to 4 (as numbered in figure 1) were most frequently used. It is possible to see that both the TReK and the voice loop displays showed large differences in the dedicated times in the beginning and end of shift. Although the staff expected a difference in these screens, it had the inverse impact, with staff using the TReK and Voice Loop screens more at the beginning than the end of the shift, contrary to expectations. The EMCS displays (screen 3) were used according to the staff expectations, showing a high usage with a tendency to be consulted more often in the beginning than the end of the shift. It was expected that the control room operators would spend more time on EMCS overview screen in the beginning of the shift to assess the status of the experiment and equipment. When an understanding is established they monitor to look for unexpected changes or trends.

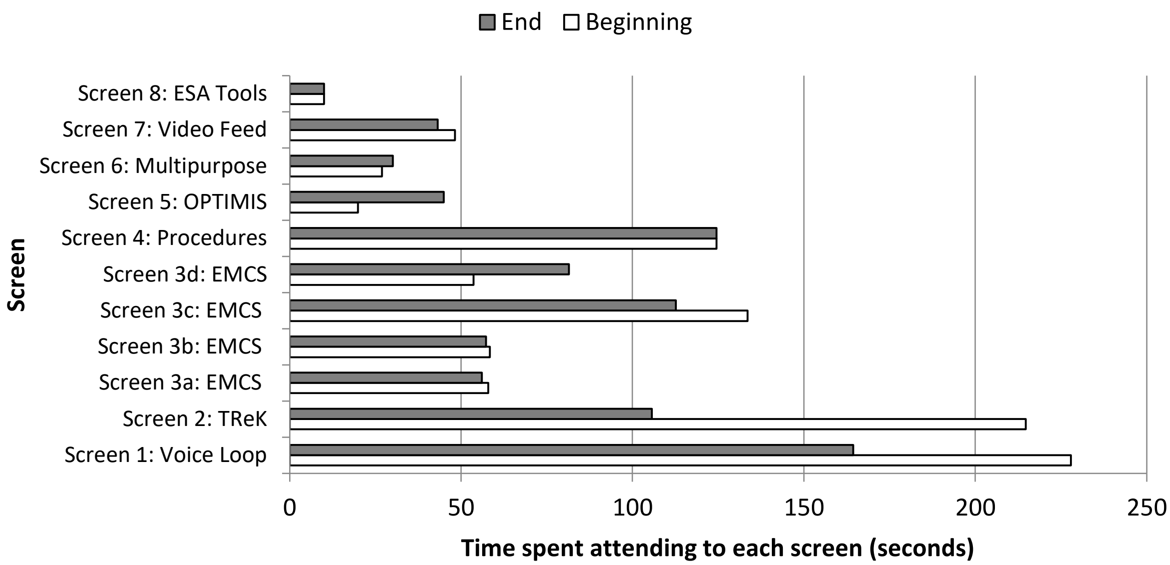

Figure 4: Average time (seconds) the participants spent looking at each of the displays in the beginning *vs* end of shift.

During this particular experiment there were some technical issues regarding the connection to NASA (displayed in screen 2), which could explain the time spent on this screen. Information about the status would be given in the handover from the operator on the previous shift, and the oncoming operator might be interested in following this closely in the beginning of the shift. The voice loop screen (screen 1) was also used more frequently in the beginning of the shift than in the end. In general the voice loop communication will vary according to (planned or unplanned) activities, either activities directly related to EMCS, or other activities onboard the ISS that might affect EMCS operations in some way (e.g. availability of crew, power or other resources). As the study did not cover all shifts it may not be possible to conclude whether the results indicate the voice loop screen is used more in the beginning of shifts in general or if it was incidental during this study.

B. Cognitive performance and fatigue

Figure 5 shows the average ratings for physical fatigue in the beginning of the shift (left) and end of shift (right). In the beginning of the shift the participants were asked to rate how they felt in a scale from 1: "Not at all" to 5: A great deal". At the end of the shift the participants were asked to rate their fatigue having the beginning of the shift as a reference and reporting whether they felt each item in a scale from 1: "Much less" to 5: "Much more", than in the beginning of the shift. The fatigue ratings were low in the beginning of the shift and did not seem to suffer a significant change by the end of the shift, with all responses being within the "no change" range (score of 3), but with most items showing a tendency for higher values at the end of the shift indicating an expected slight increase in physical fatigue.

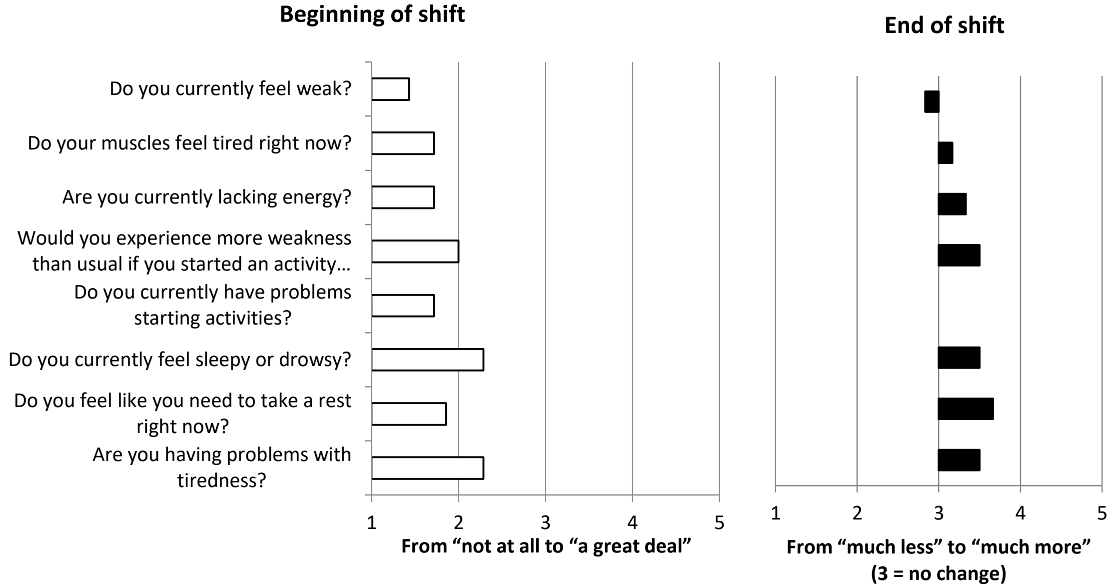

Figure 5: Average physical fatigue ratings in the beginning *vs* end of shift

Figure 6 shows the average ratings for cognitive fatigue in the beginning of the shift (left) and end of shift (right). The procedure was equivalent to the one described before for the physical fatigue. Also here the self-ratings of fatigue showed low levels at the beginning of the shift that tended to be stable also by the end of the shift with the participants not reporting any significant changes in the perceived cognitive fatigue.

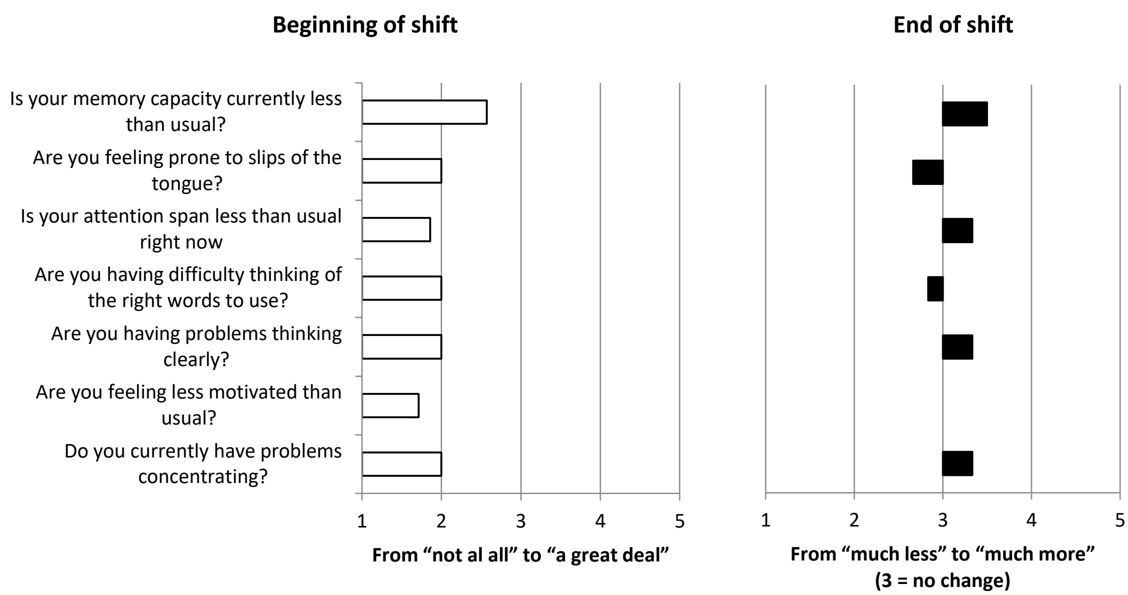

Figure 6: Average cognitive fatigue ratings in the beginning *vs* end of shift

Figure 7 shows the results of the digit span task in the beginning versus end of shift. On average the participants had a lower score in the beginning (M= 43.6, SD= 11.5) *versus* the end (M= 47.0, SD= *16.5*) of shift, which can be justified by familiarity with the task. The average time to complete the task was equivalent in the beginning (M=, SD=) and end of shift (M=, SD=). As such, the digit span task was not able to discriminate cognitive performance in the study.

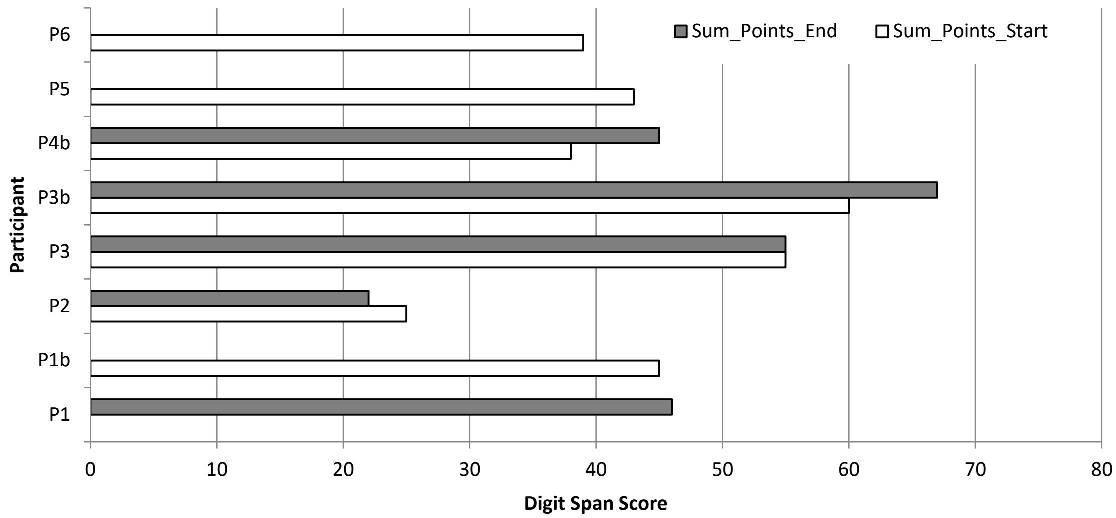

Figure 7 Results of the Digit Span Task

C. Use of the Synopticon system in the field

Figure 8 shows a screenshot of the virtual avatar of a participant during the data collection. The avatar was calibrated in the same way that the eye tracking glasses were calibrated, by looking at three points on a screen. The recording of the session could then be started.

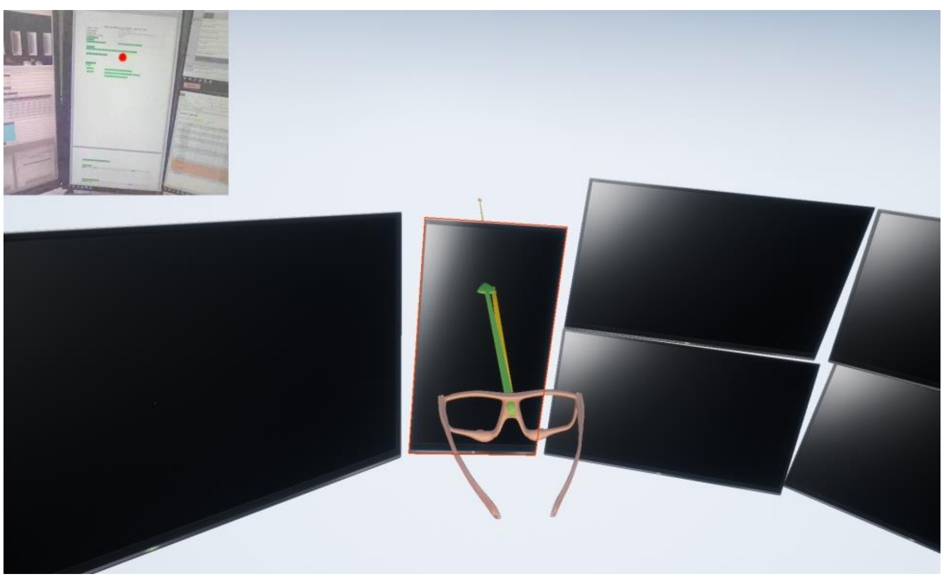

Figure 8: A screenshot of the virtual avatar of a participant.

The green arrow represents the participant's gaze and the yellow arrow shows the orientation of the glasses. In the top left corner is the corresponding video stream from the eye tracking glasses; the red dot is the location of the participants gaze. As is shown in the figure, the accuracy of the positioning system in the virtual representation is quite accurate when compared with the real world feed collected from the eye-tracking glasses and shown in the top left. The system was reliable and efficient during the data collection, allowing a live representation of what the participants were looking at. The participants reported that the glasses were not a hassle during the operations, and appear to be comfortable wearing them in the sessions.

D. Study Limitations

The study presents clear limitations that locked the findings and discussion to the restricted initially defined study goals: a preliminary assessment of the use of the new control room, and a first field test of the Synopticon system. The more ambitious goals related to the possibility of establishing links between eye-tracker markers and the perceptions of fatigue by the participants were not possible to test since the fatigue scales used in the study were not able to discriminate different states in the beginning *versus* end of shift. This might be just a methodological limitation (scales were not adequate measure of fatigue in this context) and/or it might indicate that the participants were not significantly fatigued at the end of their shifts – we were not able to identify which situation occurred here. Likewise, the cognitive performance task used did not succeed at differentiating performance in the beginning *versus* end of the shift, which once again can suggest either that the task was not sensitive to the differences and/or that the participants' cognitive performance was equivalent at the start and end of the shifts.

IV. Conclusions

The findings show that screens 1 to 4 were most frequently used which was in accordance with the expected use and the design decision to group these together. This result indicates that the use of eye-tracking as an evaluation tool of the control room design can be useful.

The findings also showed a difference on the frequency of use of the control room displays when comparing the beginning and end of each shift that was congruent with the staff's expectations for the core experiment information related to the EMCS data, especially the overview screen.

We were able to produce an online visualization of the participants' use of the screens in the new control room and to generate automatic analysis of which screens the participant's were looking and the spreads of the time spent in each display.

We were not able to establish a link between eye-tracking markers and the fatigue self-rated scales nor the cognitive performance task – these measures did not success to detect a consistent pattern in the beginning *versus* end of shift and were more impacted by the time of day when they were taken than by the targeted variable of the shift period.

In this study we were able to collected position and eye-tracking data with the Synopticon system in the field. This system enabled a quick assessment of the use of the new control center set-up with detailed objective information on which displays were being used, when, and for how long. This method can be further used an developed, being possible to set-up the system quickly and effectively to present online data on eye-tracking metrics that can be used to provide direct feedback to the people operating the systems and/or used in training contexts to improve the instructors recommendations and guidance to the pupils.

V. Acknowledgments

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