

Spatial Multimodal Alert Cues for Virtual Reality Control Environments in Industry 4.0

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ABSTRACT

The upcoming 4th Industrial Revolution (Industry 4.0) is based on data collection and analysis from mechanical equipment equipped with sensors. Typically, the operating parameters of an installation are controlled by engineers who are brought into control centers, where an array of varying size screens and instruments show the operating status of a system. This physical work environment can be replaced by a virtual reality environment, which can extend the data seen in space, 360 degrees around the engineer. In this paper, we demonstrate such a virtual environment which is based on sensor information flowing to the user in real time and focus on spatially-enabled multimodal ways to present event alerts. Using 3D audio and directed lighting to guide users attention to the alert-raising instruments, we find that the use of 3D audio, whether stand-alone or in conjunction with visual feedback, positively impacts task performance in locating and dismissing alert sources.

CCS CONCEPTS

• **Human-centered computing** → **Empirical studies in ubiquitous and mobile computing**; **Ubiquitous and mobile computing systems and tools**; **Virtual reality**.

KEYWORDS

Industry 4.0, Virtual Reality, Control Rooms, Internet of Things, Notifications, Attention Management, Cyber-physical systems

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1 INTRODUCTION

Remote monitoring and operation of complex systems, consisting of mechanical, electrical, electronic and software components, is a rapidly advancing trend. Virtual reality (VR) has been proposed as an immersive environment for tele-monitoring and tele-operation activities in a range of scenarios, including robotics [6, 9, 21, 37], unmanned aerial vehicles [3, 34], marine vessels [10, 15] and road

vehicles [11, 25, 29, 38]. Further, VR systems have been proposed as an alternative to replace traditional control rooms in large industrial installations [1, 12, 30, 31]. VR solutions for tele-monitoring offer several advantages. First, they remove the need for physical presence at or near the system to be monitored. Second, they remove the need for complex and large physical installations with fixed-size information displays. Finally, they allow the operator infinite flexibility in adapting the workspace to their current task. For example, a person monitoring a fleet of autonomous vehicles can "jump" from the control environment of a vehicle to that of another, with the immersive environment immediately adapting to accommodate the diverse arrangement of instruments present in each vehicle. The concept was demonstrated in [31] where a dynamically constructed virtual control environment was evaluated in the context of surface vessel monitoring.

Still, this dynamic adaptation of the human-machine interface (HMI), presents novel challenges for the operator that need to be addressed [19, 20]. Whether the adaptation constitutes a complete change of environment (e.g. "jumping" into a new and unfamiliar type of system), or a dynamic adaptation of a familiar environment (e.g. hiding, resizing or re-arranging some of the displays), the operator must be able to quickly identify information of interest and react to it, with help from the HMI. As stated in [12], *"Ideally, the HMI does not depend on the remote-operator's vigilance at all but directs attention quickly and effortlessly to relevant stimuli"*.

Therefore, a tele-monitoring system based in VR should provide directional cues to assist operators in the task of locating sources of information that are of interest, for example instruments whose values have gone out of normal range. To the best of our knowledge, related research on the use of directional alert cues in VR systems is presently very limited and focuses primarily on the use of visual synthetic objects [31], which obscure part of the virtual world. Less obtrusive or obstructive directional cues, using multimodal feedback, have not been previously investigated.

In this paper, we present an investigation on the use of such unobtrusive and unobstructive directional alert cues, in the form of directional rotating lighting, and spatial (3D) audio. The context of our work is a large industrial control room, such as might be possible or desired in the context of dynamic manufacturing under the Industry 4.0 paradigm, where the manufacturing or production process is decentralised and dynamically distributed across multiple physical locations [24]. Our purpose is to examine both the efficacy of such cues in assisting operators to locate sources of information of interest (alert-raising instruments), and the impact of these cues on cognitive load, which needs to be kept low during a monitoring task [12].



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2 RELATED WORK

System monitoring requires operators to continuously scan a range of instruments in order to identify sources of potential trouble. To this end, stimuli that provide information with adequate physical properties such as contrast and size are required for task success [14]. Additionally, a monitoring system that aims to assist operators in their task, should present information in a salient highlighted way, in order to reduce the effort of capturing and directing operator attention to the relevant instruments [12]. Attention can be guided by providing appropriate directional (spatial) information, which can be delivered multimodally, through visual, audio or tactile cues. While monitoring a system by directing visual attention to scan information in a range of instruments, visual events indicating alerts, such as bright light flashing, re-colouring a sign with a vivid colour, or providing animation effects to an instrument, can be effective in re-directing a user's gaze [2]. However, according to Wickens' multiple resource model [36], task performance will be impeded if multiple tasks (i.e. monitoring and searching) share the same stimulus channel. Previous research has investigated the efficacy of mapping directional information to other sensory channels in order to keep the visual channel unobstructed. For example, directional vibrotactile cues have been successfully evaluated in assisting drivers of road vehicles to avoid collisions [5, 27]. Thermal directional cues on a cane grip, have been used to assist vision-impaired persons [18]. Spatial audio has been also used for pedestrian navigation [7, 13] or collision avoidance while cycling [26].

Visual clutter in the user's information space can be very detrimental for performance in tasks that include information seeking components. Reducing the amount of information to for the user to that which is only directly relevant for the task can therefore offer distinct advantages [17]. As such, previous work has investigated the concept of gaze-adaptive interfaces, aiming to offer information at various levels of detail, only when the user requires this information [22, 23, 35]. In this work, researchers have recognised the issue of information components occluding the real, or virtual scene objects that are relevant to the user's task, thus minimisation of this occlusion is important for maintaining situational awareness and task success, in application contexts such as tele-monitoring.

While the literature on the use of VR as a tool for tele-monitoring is restricted, we can look for related work on the presentation of spatial cues in other VR application domains. One such domain is navigation, where directional arrows are probably the most obvious navigational aid. In [16], a range of non-explicit options to present spatial directional information in VR is examined against arrows, callouts, glowing paths and desaturation of surrounding scene objects. While no results on task performance were presented, researchers found that non-familiar and less explicit spatial cues (callouts, desaturation) were well received by the participants. Apart from visual information, spatial audio has also been examined in the context of VR as a tool to aid spatial awareness for users. Two separate studies by Valzoger et al. [32, 33] demonstrate that three-dimensional and monaural sonification of objects in VR makes localisation of these objects easy for users. Further, the use of spatial audio as a wayfinding aid for both sighted and non-sighted users in VR environments has been demonstrated to be a viable

alternative, showing that cognitive capacity for continuous processing of spatial audio information is a modality channel worth exploring [4, 8, 28].

Summarising, in the context of VR-based tele-monitoring, spatial cues are important to aid users in locating the information displays that are relevant to their task. Spatial cues can be presented visually (e.g. as arrows or instructions) but this occludes the scene and may increase the cognitive load of the operator. In this paper, we hypothesise that less obtrusive spatial cues in the visual and audio modality could be effective in providing the spatial awareness needed for task performance, and compare two novel methods for tele-monitoring, namely directional rotating lighting, and spatial (3D) audio.

3 SYSTEM DESIGN

We implemented a virtual control room using the Unity Engine and the Oculus Quest 2 VR headset. The control room is populated with instruments of three types: Numeric displays, Needle displays and Bar displays. The displays extend 360 degrees around the user and are placed on virtual walls that surround her. The user is seated in a virtual chair and can freely look around in all directions, but cannot move in the VR environment. Near the user's position, a set of consoles contains virtual buttons with each button associated to a corresponding instrument (see Fig. 1.)

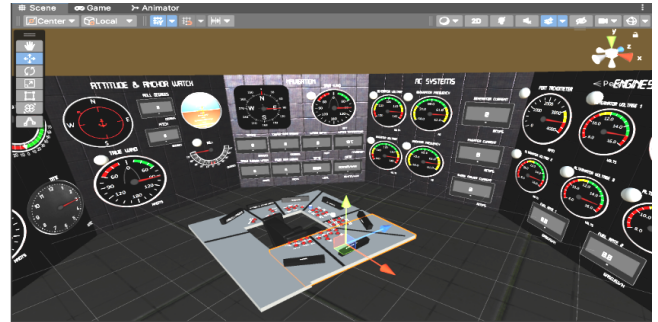


Figure 1: Overview of the control room environment. The user is positioned in the virtual chair in the middle of the room.

Each instrument is associated with a range of values, for which a specified part is demarcated as being outside the "normal" range (values are either too low, or too high). Each instrument's value is constantly updated through a script that generates random "normal" values, and occasionally produces an out-of-range value for that instrument. When an out-of-range value is produced for an instrument, the user can simulate correcting the problem by pressing the console button corresponding to the instrument. The action is performed through the hand-tracking capability embedded in the VR headset, and the user can see their simulated hands in the VR environment (Fig. 2).

When an instrument produces an out-of-range value, a related multimodal alert is issued. Alerts are of three types: Visual, 3D Audio and Mixed (a combination of the former two). Visual alerts are produced by placing a rotating light source on the instrument, akin to those in emergency vehicles (e.g. ambulances, fire-trucks

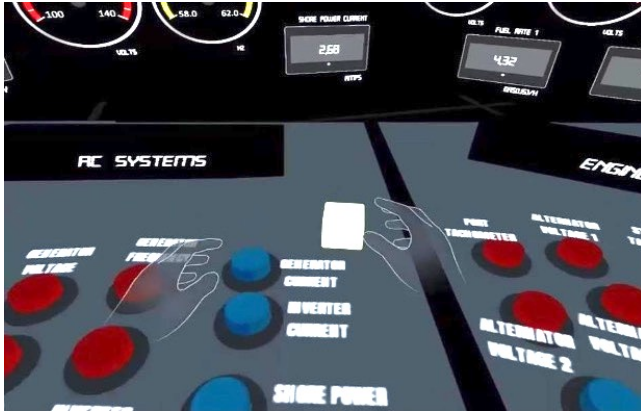


Figure 2: Virtual user hands and console buttons

etc), see Fig. 3a. The light source rotates in a clockwise or counter-clockwise manner, depending on the orientation of the instrument to the user's current direction of vision. Therefore if the instrument is to the left of where the user is currently looking, the light rotates counter-clockwise, illuminating the walls and therefore allowing the user to understand that the instrument is to their left. 3D (spatial) audio operates in a similar manner, allowing the user to comprehend the direction of the instrument. The audio is an intermittent buzzer sound (Fig. 3b).

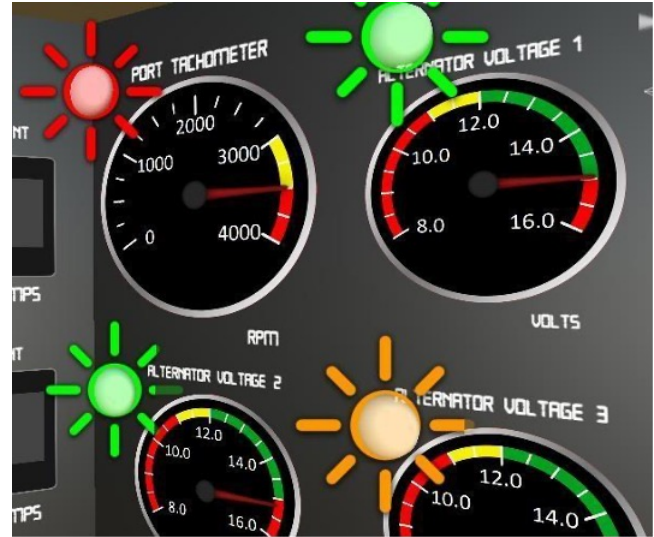
Instrument alerts are also associated with three levels of importance (danger), low, medium and high. These importance levels are communicated to the user by using different colors when a rotating light is activated (green, yellow and red respectively). For the 3D audio alerts, the buzzer interval is also modulated accordingly (long, medium and short intervals respectively).

4 EXPERIMENTAL RESULTS

4.1 Experiment design

We conducted a within-subjects design experiment to assess the effect of visual or audio guidance to the instruments generating alerts, with three conditions: Visual, Audio and Mixed alerts. Each participant performed a session under each condition, with 10 alerts of the related condition issued during the session at random timings. Therefore each participant had to identify the source instrument and dismiss by pressing the relevant button for $3 \times 10 = 30$ events in total. To avoid learning effects, we used a *balanced* latin square design to determine the order of conditions presented to participants.

To perform the experiment, after consent had been sought, participants began with a simple demographics form, followed by an execution of three benchmark tests for reaction time, sequence memory and visual memory, in order to remove participants that might exhibit divergent capabilities and ensure sample homogeneity. Each participant performed three rounds under each test. We then demonstrated the system to participants by using the system ourselves and allowing participants to view the displayed scene on an external monitor (Fig. 4). We clarified any questions and proceeded to allow the users some free time (until they were ready)



(a) Implementation of visual alerts.



(b) Implementation of audio alerts.

Figure 3: Implementation of the visual (top) and audio (bottom) alert system.

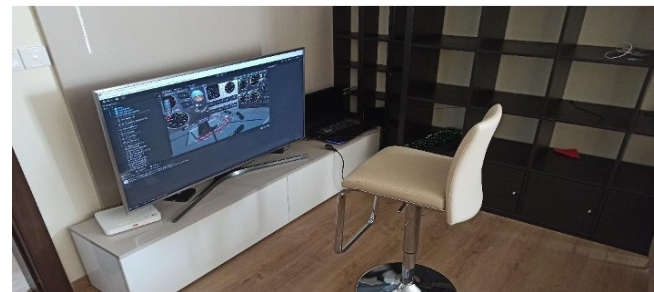


Figure 4: Experiment environment. Participants sit at the stationary rotating chair. Researchers can monitor participants behaviour by observing the large monitor that mirrors the participants' view in the VR environment.

with each condition, prior to starting the session related to that condition. A NASA-TLX questionnaire was issued at the end of each session. Finally, an exit questionnaire was administered, at the end of the experiment.

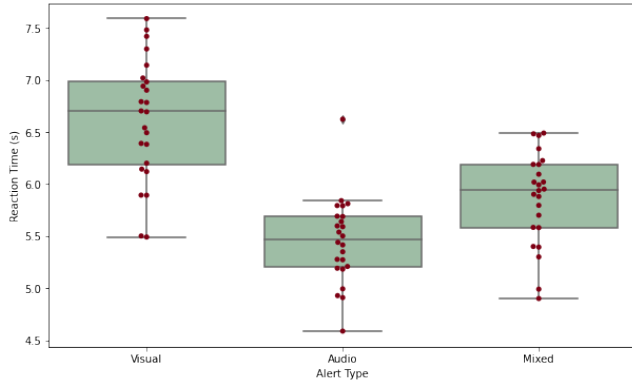


Figure 5: Mean reaction time to events per condition.

4.2 Participants

For complete balance this design requires the number of participants to be a multiple of 6 (since we have 3 conditions). An a-priori computation of sample size showed that 22 participants would be enough to detect large-sized effects with statistical significance (study power $1 - \beta = 0.95$), therefore determined we could recruit 24 participants to satisfy the balanced latin-square arrangement and have a chance to achieve statistically significant results. We recruited 24 (9 female) participants, all employees of a software engineering company, with an average age of 28 ($\sigma = 3.724$). Nine participants indicated having used VR headsets on prior occasions, but only three own such equipment. We examined their performance in the human benchmark tests. All participants mean performance in the three rounds of each test were within one standard deviation from the sample mean (reaction $\bar{x} = 250.764\text{ms}$, $\sigma = 16.186$, sequence memory $\bar{x} = 10.319$, $\sigma = 1.042$, visual memory $\bar{x} = 10.625$, $\sigma = 1.152$). Therefore we did not exclude any participants from the analysis.

4.3 Results

The results were analysed using appropriate statistical tests chosen after examination of the assumptions for their use. Analyses were executed using SciPy 1.10.1 (Python) and IBM SPSS v27 software.

4.3.1 Quantitative results. The mean reaction time to events (issue until dismissal) was lowest for Audio notifications ($\bar{x} = 5.453\text{s}$, $\sigma = 0.402\text{s}$), followed by Mixed ($\bar{x} = 5.868\text{s}$, $\sigma = 0.432\text{s}$) and Visual ($\bar{x} = 6.617\text{s}$, $\sigma = 0.576\text{s}$), as shown in Fig. 5. An ANOVA test ($F_{(2)} = 35.310$, $p < 0.001$) demonstrated that these differences were statistically significant. Further pairwise t-tests with post-hoc Bonferroni correction (adjusted p -value threshold at $p = 0.16667$), indicated statistically significant differences between Visual and Audio ($t = 11.026$, $p < 0.001$), Visual and Mixed ($t = 6.695$, $p < 0.001$), and Audio and Mixed ($t = -3.672$, $p = 0.0013$).

As a next step, we examined whether the alert importance (low, medium or high) had an effect on the reaction time for each condition. As shown in Fig. 6, we notice that participants are consistently quicker to react to higher importance events under the same modality. A two-way repeated measures ANOVA on alert modality and

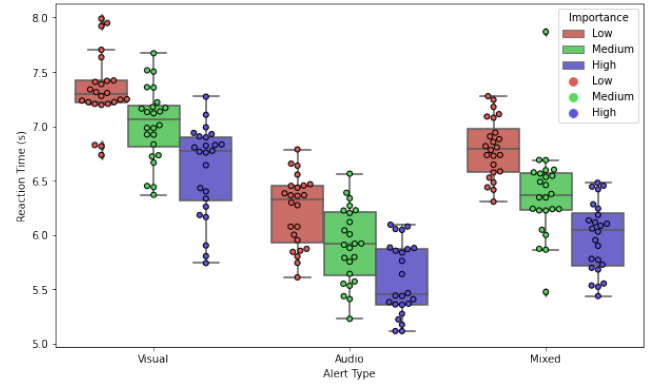


Figure 6: Mean reaction time to events per condition and alert importance.

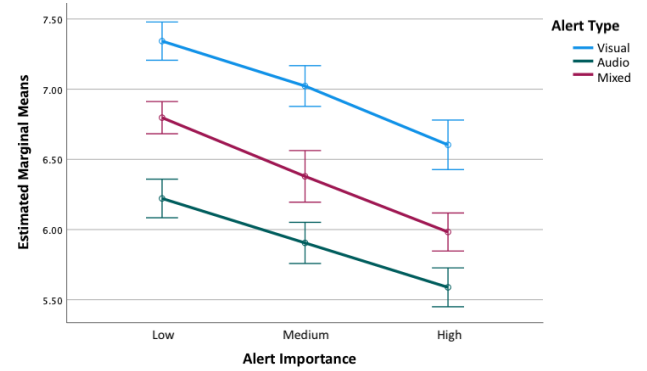


Figure 7: Interaction effects of the two-way ANOVA alertmodality \times alertimportance.

alert importance (dependent variables) against reaction time (independent variable) showed a statistically significant main effect of modality on reaction time ($F_{(2,46)} = 129.124$, $p < 0.001$), in line with our previous finding (Fig. 7). Additionally, we found a statistically significant main effect of alert importance on reaction time ($F_{(1,612,46)} = 170.673$, $p < 0.001$, Greenhouse-Geisser corrected). Finally, we examine the interaction effects alertmodality \times alertimportance but do not find any statistical significance ($F_{(4,92)} = 0.657$, $p = 0.623$), therefore the impact of alert importance is the same across all modalities.

4.3.2 Subjective Feedback. Further to the analysis of objective data, we examine participants' feedback using the NASA-TLX questionnaire (Fig. 8). Across all axes, we note that participants perceive the Mixed modality condition to be the most taxing, with no clear advantage to performance, at least compared with Audio alerts. Mental load is lower for visual alerts compared to audio alerts but not mixed alerts, indicating that locating the source of the alert was perceived to be easier with the visual cue compared to localising with the 3D audio. This is also reflected in participants' perception on the time it took them to locate the alert source, which was

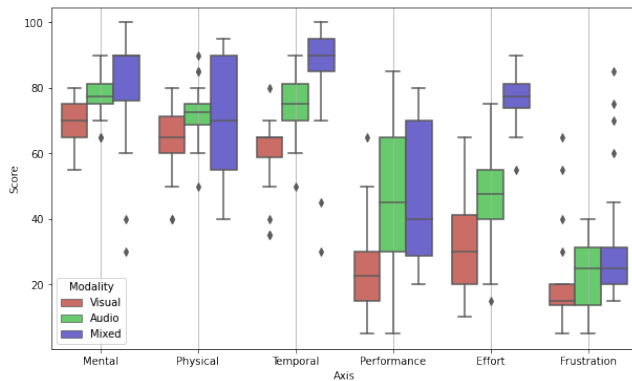


Figure 8: NASA-TLX reported score averages per instrument axis.

consistently reported lower with visual alerts. Interestingly, this subjective assessment is counter to the actual time it took participants to react to alerts, since as we saw earlier, this was highest with visual alerts (Fig. 5). On the other hand, participants judged their task performance to be best with audio and mixed alerts, though both required more effort. Frustration was the same for modalities and we note that it is reported to be relatively low.

5 DISCUSSION AND CONCLUSIONS

In this paper, we sought to understand how less explicit directional cues might assist future engineers perform monitoring tasks in a VR environment, in the context of Industry 4.0. Our results indicate that both multimodal techniques we designed were effective towards assisting users to find the desired information in the VR control environment, although spatial audio seems to present a better advantage both in terms of task performance, and cognitive load factors related to achieving this performance. The combination of visual and audio cues is also better compared to the visual cues alone, but not as good as the isolated audio cues. Compared with previous literature, the closest related work to ours is [31], which used directional arrows to guide users to information in a VR control room. In this paper, participants achieved a mean reaction time $\bar{x} = 15.571s$, $\sigma = 5.783s$, which is almost three times as high as in our experiment (Audio notifications $\bar{x} = 5.453s$, $\sigma = 0.402s$). These results verify the findings of previous literature that suggest that detailed visual information for spatial awareness may pose significant additional load on the already loaded visual perceptory and cognitive channel.

These results mean that in the context of an information-rich environment, spatial awareness can be successfully supported without the need to clutter the visual scene and add more layers of information on an already loaded perception channel. In contexts where audio monitoring might be important (e.g. listening for certain sounds), the rotating light can offer a viable alternative. In contexts where the audio perceptory channel is not required as part of the monitoring process, further advantages can be reaped by using this channel to provide spatial awareness to assist information finding.

Our work is limited by the artificiality of the simulated environment. Of course, participants were not under real pressure to find

and react to information quickly, although the results, as broken down by alert importance, demonstrate that the participants took the task seriously and reacted in the expected manner. Further, the experiment was limited to the time available to participants and was conducted in just one session. It would be interesting thus, in the future, to examine whether longitudinal exposure to the environment and increased familiarity of participants with the location of instruments and spatial cueing, has a further impact on task performance. Finally, we would like to examine further aspects of tele-monitoring conditions, such as collaborative environments with multiple operators and different contexts of operation, e.g. room size, ability to move around the room, and distinct application case studies (e.g. industrial facility, marine vessel, hospital patients etc.).

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Table 1: Statistical test results for NASA-TLX. Statistically significant results are in bold (*<0.05, **<0.01, *<post-hoc Bonferroni correction threshold).**

	ANOVA F, p	VIS-AUD t, p	VIS-MIX t, p	AUD-MIX t, p
Mental	4.022, 0.022*	-3.218, 0.004***	-2.460, 0.022	-0.689, 0.498
Physical	2.803, 0.068	-	-	-
Temporal	25.044, <0.001**	-5.722, <0.001***	-6.233, <0.001***	-3.012, 0.006***
Performance	9.220, <0.001**	-4.046, 0.001***	-4.163, <0.001***	-0.062, 0.951
Effort	72.964, <0.001**	-2.787, 0.010***	-12.301, <0.001***	-8.962, <0.001***
Frustration	4.698, 0.012*	-0.551, 0.587	-2.293, 0.031	-2.518, 0.019

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