Monitoring Maritime Industry 4.0 Systems through VR Environments

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ABSTRACT

In this paper, we present a novel system aimed at replacing large-display information dashboards in industrial control rooms, with a flexible, dynamic and reconfigurable immersive virtual reality environment, which can afford high mobility without constraints, to remote engineers. In this context, we investigate the role of semantic and spatial cues for delivering event notifications within the control environment, and present empirical evidence from a controlled laboratory study, simulating a marine industrial environment. We find that spatial and semantic cues can both offer significant benefits to operator awareness and their combination can significantly improve the findability and response time to particular information in the extended information space surrounding the user.

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

Industry 4.0 is heralded as the next evolution in industrial systems, which introduces the concept of cyber-physical systems (CPS) as an integration of hardware, software and people, aimed to improve the flexibility and robustness of industrial processes through increased digitisation [27]. In its core, Industry 4.0 focuses on the interconnection of sensors, devices, machines and processes, creating an Industrial Internet of Things (IIoT). The aggregation of information from various industrial components allows the construction of Digital Twins (DT), which are real-time virtual representations of a physical object, system or process [20]. Digital Twins allow the precise tracking of industrial systems performance and behaviour, and, since the process is entirely based on Internet technologies, this monitoring can be carried out from any location.

The remote monitoring ability afforded via Digital Twins is a stark contrast to the industrial control rooms that are typically associated with industrial processes, and which are comprised of fixed installations (e.g. a dedicated control or operations room). Furthermore, because of the ability to digitally access information for any industrial component, DT-based monitoring environments can be fully digital and information, in the shape of digital instruments, can be flexibly arranged and re-configured to suit individual workspace and human operator contexts. A typical example of this process is the digital dashboard, often configured to fit a single or multiple desktop monitors (e.g. as in [30]). Digital dashboards can also be configured to fit wall-size displays, but a shortcoming of both approaches, is that human operators still need physical access to stationary equipment of appropriate size, in order to carry out their job. Mobile device oriented versions of such digital dashboards can afford truly mobile remote access to information, but the limited screen size reduces the amount of information that can be intelligibly displayed, and interaction demands increase as the human operator is required to "flick-through" multiple screens of information, in order to find desired components [31].

Another possibility for remote and flexible monitoring of industrial systems through the digital twin concept, is the use of virtual reality technology (e.g. [36]). Contrary to desktop or mobile-based systems, VR systems offer an infinite display area extending spherically around the user, presenting a fully synthetic environment, which can thus be completely and flexibly reconfigurable. Compared with large, or multi-monitor displays, use of a VR headset does not require extensive workspace, or costly installations [32].

Additionally, VR systems can be highly mobile at the cost of some display resolution, through the use of smartphone-based VR headsets. These systems comprise of a headset (viewer), in which a user's smartphone is inserted. The smartphone screen is used to display stereoscopic visuals by splitting the screen in two, which the user can view as a fully immersive 3D image, with all the benefits of depth perception.

In the context of this paper, we explore the use-case of naval vessels (large ships) as increasingly important application of Industry 4.0, not only as part of a value and supply chain, but mostly as systems themselves. Commercial vessels are, in essence, complex floating industrial installations, requiring a large and experienced crew to coordinate multiple subsystems (e.g. electrical distribution and power generation, mechanical propulsion, navigation, docking, loading, refuelling etc.). As such, they are prime candidates for increased automation and may benefit substantially from integrating IIoT and DT technologies, as a means to simplify and improve on-board operations [11]. Further, commercial ships travel worldwide and there is an expressed need for their base of operations to be aware of potential problems, in order to schedule maintenance, repairs and itineraries. In the future, it is very likely that we will witness the proliferation of unmanned (drone) ships, just as we are currently witnessing the proliferation of civilian and military unmanned aerial vehicles, meaning that effective remote monitoring and control of their operations will become of essence [38]. Drone ships are already emerging as solutions for high-risk operations (e.g. the SpaceX sea-based landing platform), but due to the potential savings to the maritime industry, they are set to become mainstream in areas such as freight transport.

Motivated by the exciting opportunities that VR systems can afford in Industry 4.0 monitoring scenarios, and particularly by the potential that can be afforded for the maritime industry, our paper presents a novel VR-based monitoring environment for ships. Such a system could be used both on-board, affording crew members uninhibited monitoring ability from anywhere on the ship (in the case of manned vessels), and also remotely, affording remote engineers and operations staff a real-time connection with a ship and all its systems (in the case of both manned and unmanned vessels). Our virtual environment extends 360 degrees around the user, which means that emergent events displayed in instruments outside the user's field of view, may not be easily noticed. In this paper, we focus specifically on the presentation and interaction of users with notifications about emerging events in this rich information space.

2 PREVIOUS WORK

A wealth of literature exists on the topic of interruptions and attention management in computer systems. We present first a basic background to contextualise our paper within the literature, and then discuss recent related work that focuses on attention management in VR environments.

2.1 Attention management

Modern life is rife with technology-based interruption, in both personal and professional activity contexts. Interruptions may be related to the user's current main activity, or they may be related to other events taking place simultaneously. In all cases they may be considered as unpredictable, external events, which have a negative impact on the user's focus on their primary task [35]. Interruptions during use of a computer system may be generated by multimodal notification alerts which are completely unrelated to the current task, alerts that relate to tasks being attended to in parallel to the main task, or reviewing alerts, which can be used to remind users of actions related to the current task, or to maintain focus on the current task [19]. In a taxonomy of interruptions presented in [1], interruptions that relate to the current main task are termed as *interventions*, while others can be considered to be *intrusions*. Further, interruptions can be categorised according to their nature as informational or actionable, and thus, by combination, interruptions can be classed as a) informational interventions, b) actionable interventions, c) informational intrusions and, d) actionable intrusions. A further subtype (system intrusions) is used in [1] to distinguish interruptions caused by the IT equipment being used and relates to its available resources or state. Focusing on the paper's goal, we are mostly concerned with the intervention category, which supports a user's main task. In this context, notifications that raise interruptions contribute to performance detriments, but may also be extremely necessary, since intense focus on a task (or object) may lead to *inattentional blindness* to important information about state changes displayed elsewhere [34]. A notification can provide more value to the user, if it provides spatial cues about the location of the secondary task to which the user's attention is diverted, and also semantic cues, which may include colour-coded information (e.g. for urgency) and textual descriptions of the event [9].

2.2 Virtual reality for data visualisation

Space is essential for the organisation, distribution and management of information in physical, as well as digital workspaces, helping users make better sense of complex and interrelated information [3]. An extension to the use of large digital displays is the use of VR technology, which can offer unprecedented abilities to manipulate and arrange digital information [23, 25]. Examples of the use of dynamically reconfigurable displays for VR can be seen in map-based applications [2, 5, 16] or immersive analytics [37]. Past investigation of the use of VR spaces to provide large information layouts has uncovered a range of issues related to their use. These issues include the limited interaction modalities, problems with mobility in the real world, graphics quality of the visualisations and physiological issues (e.g. eye strain, motion sickness) related to interacting with immersive environments [8, 24, 26].

VR has been proposed as a fundamental tool in the context of Industry 4.0 [10, 18]. Its use varies from data visualisation and exploration [6, 7], visualisation of equipment operation [12, 22] and training [21, 28]. In [4, 13, 14, 33, 39], VR has been used to immerse users in faithful reproductions of actual control rooms, in order to investigate ergonomics issues or address training needs. We haven't, however, been able to find related literature on the use of VR as a substitute for industrial monitoring environments, such as the large displays and multi-monitor workstations placed in dedicated rooms.

2.3 Attention management in virtual environments

Attention management in VR spaces is another area of research which has received little attention in recent literature. In [15] the authors discuss that notification systems implemented in commercial VR headsets follow the simple solution of presenting information in a 2D pop-up panel, floating at a fixed distance from the user's viewpoint. It is argued that this display style may not necessarily translate well to the immersive sensation sought in VR applications, but in our case, complete immersion is not a high-priority target. The authors propose some fundamental design guidelines from their findings, including the need to reduce visual search, to provide dismissible notifications, and to make notifications easily distinguishable from other synthetic world objects. In [29], the authors examined multiple notification panel placements in the virtual world. Amongst the design options, a videogame-like head-up-display panel scored best for noticeability, reaction time, and not missing notifications. This was also verified in a later study by [17]. In [40], alternative options for presenting notifications in a more immersive manner are presented, which may provide interesting inspirations since the notification may be accompanied (or wholly replaced) by manipulations of the world objects (e.g. through dimmed lighting everywhere apart from the object relating to the notification).

2.4 Summary

While VR has been proposed as an essential technology for Industry 4.0 applications, its use to replace the traditional control-room environment or large-display dashboard monitoring systems has not yet been investigated in literature. Previous work demonstrates the potential of VR as a display technology that can increase the ability of users to explore and comprehend complex information spaces. Past work in VR notification design provides basic guidelines about the design of visual alerts in such spaces. This background sets the theme for our paper, which is to investigate the use of VR technology to extend the information space in an Industry 4.0 monitoring context, and examine notification design to increase operator awareness in such environments. We present the following hypotheses to be examined in the rest of the paper:

H1: The addition of a spatial cue can have an effect on the participants response time to notifications in a VR control room environment.

H2: The response time to notifications can be affected by the angle between the participant's viewpoint and the event-raising instrument at the time of notification issue.

H3: The response time to important notifications can be affected by semantic cues for notification priority (colour coding).

3 SYSTEM DESIGN

Our system is based on three major components (Figure 1). For the collection, processing and management of IoT data, we use an instance of the open-source ThingsBoard platform. The platform allows for the effective management of incoming datastreams via multiple protocols (e.g HTTP, MQTT, OPC-UA), and the pre-processing of data through rule-based customisations (e.g. to remove corrupt or redundant data or to transform data before storage). The IoT platform has the ability to publish incoming datastreams (with or without processing) to the Apache Kafka distributed event streaming platform, which we employ in order to provide subscription-based updates to the data consuming application used to power monitoring dashboards. Data pushed to the Kafka stream can be packaged with a range of metadata, including the instrument it concerns, whether the data value is out of normal range, the level of criticality of the event and so forth. This additional data is provisioned through the ThingsBoard rule engine by processing incoming data as it arrives at the platform. For the presentation of information to human operators, we wrote a custom application in Unity (using C#) which is able to consume data from the Kafka stream and present this information in the form of digital instruments (gauges, readouts, text etc.) across multiple desktop spaces (e.g. a video-wall or a multi-monitor workstation), and in the form of a VR space, which is the subject of our paper.

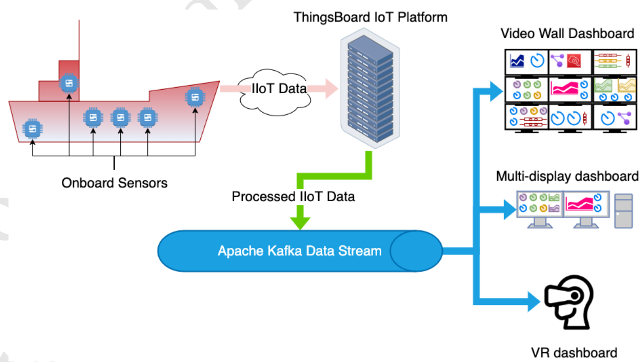

Figure 1: Overview of our system architecture.

3.1 VR Control Room

The VR control room is designed as an octagonal walled space extending 360 degrees around the user's view, with each wall dedicated to displaying instruments related to a specific function of the vessel (Figure 2). One of the walls doesn't display any instruments, but is covered by a video stream panel, so that streaming video from a camera can be displayed (Figure 3). The user is positioned in the centre of the room. The user can move their head to look around the room but the user's position in the room remains fixed to its center, as there are no other controls for moving around the room. The virtual dimensions of the space are such that when the user is directly looking at the centre of a wall, they have in their field of view (FoV), that entire wall plus approximately half of the two laterally adjacent walls. The user has the whole height of the wall in their FoV. A white dot at the centre of the user's FoV shows the user the center point of the camera view. Further, the red panel on the top left of the screen shows some basic statistics (time elapsed, notifications issued etc.) and remains fixed in this position of the user's FoV as they move their view around.

3.1.1 Presenting event notifications with semantic cues. When a particular sensor sends data which is evaluated as appropriate for raising an event, this information gets passed through the Kafka

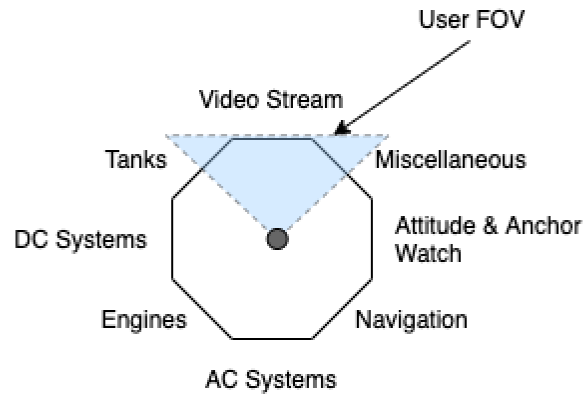

Figure 2: Schematic of the VR control room layout.

Figure 3: View inside the VR control room. The mobile screen is split in two, to display the stereoscopic image.

pipeline to the dashboard application. In the context of the VR control room, we choose a unimodal (visual) presentation of the event to the user, which is achieved through a colour-coded stacked list on the bottom right of the user's FoV (Figure 4), providing thus semantic cues to the user as per [9]. The notification stack remains fixed in position in the user's FoV, following the videogame-like HUD guideline as per [17, 29]. Items are added on top of the stack as they arrive, in chronological order. Each item in the stack is color-coded for event severity (green, orange, red). Two lines of text show the name of the instrument related to the event, and the name of the wall on which this instrument can be found.

3.1.2 Notification dismissal. The user can dismiss a notification (remove it from the stack) by placing the FoV-centre white dot anywhere on the instrument related to the notification, and keeping it there for 5 seconds. When the user places the white dot on an instrument related to an event pending in the stack, the dot changes to a display a countdown in seconds for the time needed to fixate on the instrument. This process emulates the user's engagement with a particular job, perhaps not in a very realistic way, but definitely enough to simulate the shift of attention (focus) on a specific aspect of the UI, much like what might happen in real life during an event.

3.1.3 Spatial cues. As a further means to assist the user in locating an event-raising instrument was implemented, by providing a spatial cue, as per [9]. This was achieved with a 3D arrow, which can be optionally presented on the top centre of the user's FoV. This arrow rotates to point towards the direction of the current most critical notification, regardless of when it was issued. If there are multiple notifications with the same criticality (e.g. two reds), the arrow points to the one issued first.

3.1.4 Demonstration and code availability. A video demo of our system can be viewed at https://youtu.be/QVlVL1p4pjI. The developed VR client runs on Android devices (version 10 and above) and can be downloaded as an APK from http://www.komninos.info/marineVR/vrmonitoring.zip. The client does not require a ThingsBoard instance to run, as it generates random events from within the application for demonstration purposes. The complete source code for the VR client is available on request.

Figure 4: Display of notifications stack in the VR control room

4 EVALUATION

4.1 Experimental conditions

4.1.1 Experiment design. We designed an experiment with an aim to investigate the role of spatial cues (namely, the presence of the 3D arrow) in handling notifications in the VR control room environment. Therefore our experiment involves two conditions, "Single Cue" (SC) involving presentation with semantic cues only, and "Multiple Cues" (MC), involving presentation with both semantic and spatial cues. The experiment followed a repeated measures approach, with participants experiencing both conditions in a counterbalanced manner, in order to mitigate learning effects. Each participant was asked to perform five sessions under each condition, with each session having a duration of 3 minutes, resulting in a total of 10 sessions per participant. For the purposes of the experiment, we "fed" the system with data from generator scripts (not real sensors), which were tuned to probabilistically generate approximately 10 anomalous data events every 3 minutes (i.e. the duration of each session). Therefore each participant would attend to approximately 100 notifications across both conditions.

4.1.2 Procedure. At the start of the experiment, participants filled in appropriate consent and basic demographic forms. Participants were then seated safely in a rotating office chair, in an obstacle-free environment. Before the actual experiment, participants were exposed to the VR environment for an unrestricted amount of time (until they felt they had familiarised themselves with it). During the familiarisation process, we adjusted the headset straps and lenses to ensure participant comfort and viewing clarity, explained the basic principles of operation and answered any questions about the system. For the experiment, we instructed the participants that they should focus on the video stream and watch it, while no notifications were active in the experiment. We also instructed them to immediately tend to notifications by locating the necessary instruments, and to try to dismiss higher priority notifications before tending to others. To prevent VR-sickness issues, we allowed participants to rest for at least two minutes between sessions and for at least five minutes between conditions, or for as long as they needed before feeling ready to proceed.

4.1.3 Materials. The equipment used for the study was a Xiaomi Redmi 8 Note Pro smartphone, with an Archos VR headset used to attach the smartphone and deliver the experience. Since the device splits the view in order to create the stereoscopic effect, the effective resolution of the display was 1170 x 540 pixels (half the original screen resolution of 2340 x 1080) which was adequate to provide good legibility of text in the application.

4.1.4 Participants. We recruited 17 participants through convenience sampling at our university department, aged between 25-38 years old (3 female). None of the users were familiar with marine vessel systems. Most participants (14) had never experienced VR in the past.

4.2 Data collected

For each notification, we collected the experiment condition, session number, notification generation timestamp in milliseconds, the notification priority, the instrument related to the notification, the horizontal plane angle between the user's FoV centerpoint and the instrument relating to the notification (as a means to capture how much the user's head had to turn to find the instrument, see Figure 5) and finally the number of ongoing (active) notifications at the time of issue. We also recorded the timestamp at the moment of notification dismissal, and the number of active notifications at the time of dismissal. We noticed in a few instances that some captured data was corrupted and we removed these cases from the dataset. Since notifications are generated in a random manner, some participants might experience more notifications in a given session than others. The number of notifications in sessions ranged from 3 (1% of all sessions) to 10 (42%), with 96% of all sessions having 5-10 notifications (8-10: 75%), thus we consider the exposure of participants to the conditions satisfactory. In total, we collected data for 646 notifications in the SC condition, and 558 notifications in the MC condition.

4.3 Empirical findings

In the following analyses, statistical tests are chosen after checking whether the required assumptions hold (e.g. normality, skewness etc.).

4.3.1 Effect of spatial cue on response time. We first take a high-level view on the data, by examining whether the presence of a situational cue has an effect on notification response time. The mean response time across all user sessions is longer in the SC

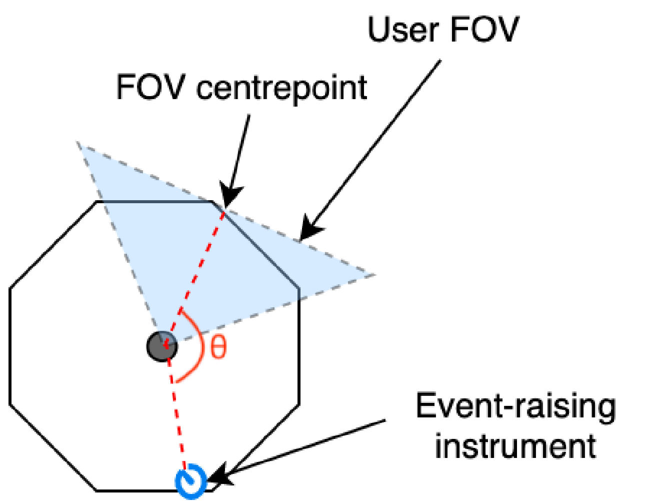

Figure 5: Horizontal plane angle θ between user's FOV centrepoint and an event-raising instrument.

condition ($\bar{x} = 24.801s, s = 9.998s$) than in the MC condition ($\bar{x} = 19.991s, s = 10.585s$) as shown in Figure 6, representing a medium effect size ($d = 0.467$). A Wilcoxon signed-rank test however revealed that this difference is not statistically significant ($Z = -1.160, p = 0.246$). Further breakdown of the response time according to session ID reveals a learning curve (Figure 7) with participants performance improving continuously until session 4. The last session has increased response times, which could be attributed to participant fatigue during the experiment. To obtain a clearer result of participant performance, we repeat the statistical testing procedure, using only data from sessions 3-5 into account. In this case, we note that, again, on average the response time is slower in the SC condition ($\bar{x} = 19.790s, s = 6.466s$) than in MC ($\bar{x} = 15.571s, s = 5.783s$), again representing a medium effect size ($d = 0.69$). The difference this time though is statistically significant (Wilcoxon signed-rank test, $Z = -2.059, p = 0.039$). For the rest of the analysis, we proceed with data from sessions 3-5 only.

4.4 Effect of angle between user's FoV and instrument

Hypothesis 2 is founded on the assumption that the response time to a notification might increase with the viewing angle, since the user's body will need to rotate more to find the relevant instrument when this angle is larger. We recorded angles as signed floating-point values to indicate the direction (left or right), but for this analysis we employ the absolute value, since the rotation direction is irrelevant. For this, we perform a Spearman's correlation test between the observed response time and angle in each condition. In both cases, a correlation cannot be established with statistical significance (SC $\rho = -0.400, p = 0.112$, MC $\rho = -0.142, p = 0.586$).

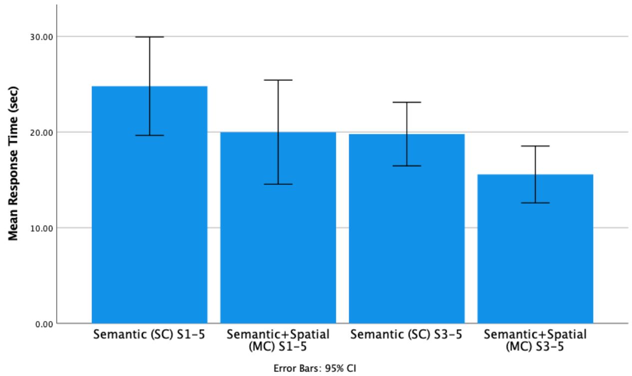

Figure 6: Mean difference of response time across conditions, using data from all sessions (first two bars) and data from sessions 3 to 5 only (last two bars).

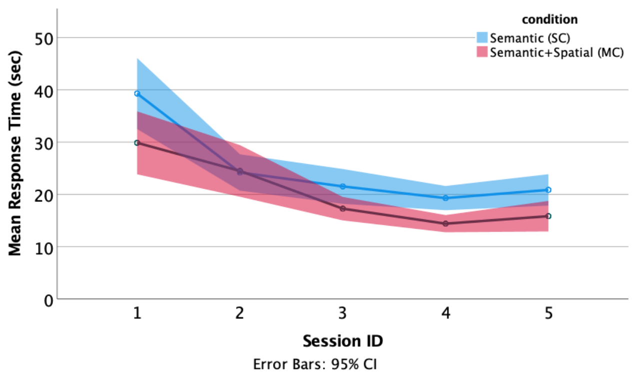

Figure 7: Mean response time across sessions.

4.5 Effect of semantic cues on response time

Next, we examined user response time based on notification priority, since our instructions to participants were to attend to higher-priority notifications first. As can be seen in Figure 8, users exhibit lower response times for more urgent notifications in both the SC condition (Low priority $\bar{x} = 21.851s, s = 7.682s$; Medium priority $\bar{x} = 18.911s, s = 8.607s$, High priority $\bar{x} = 16.821s, s = 6.814s$) and also in the MC condition (Low priority $\bar{x} = 21.851s, s = 7.682s$; Medium priority $\bar{x} = 15.352, s = 5.148s$, High priority $\bar{x} = 12.342s, s = 4.575s$). Although in both conditions we notice the same trend, the differences in response time across priority levels within the SC condition is (marginally) not statistically significant (Friedman test, $\chi^2_{(2)} = 4.507, p = 0.105$), while the same test shows a statistical significance exists within the MC condition ($\chi^2_{(2)} = 15.176, p < 0.001$). Pairwise Wilcoxon signed-rank tests with post-hoc Bonferroni correction (setting the p-value threshold to 0.017 shows that a statistically significant difference exists between the mean response times of Low vs. High and Medium vs. High priorities within the MC condition (Medium-Low $Z = -1.704, p = 0.088$, High-Low $Z = -3.337, p < 0.001$, High-Medium $Z = -3.195, p < 0.001$). On the other hand, comparing the mean response time for the same priority level across each condition, we note that while response time is generally lower in the MC condition, these differences are not statistically significant (Wilcoxon signed-rank tests, Low priority $Z = -1.681, p = 0.093$, Medium priority $Z = -1.775, p = 0.076$, High priority $Z = -1.917, p = 0.055$).

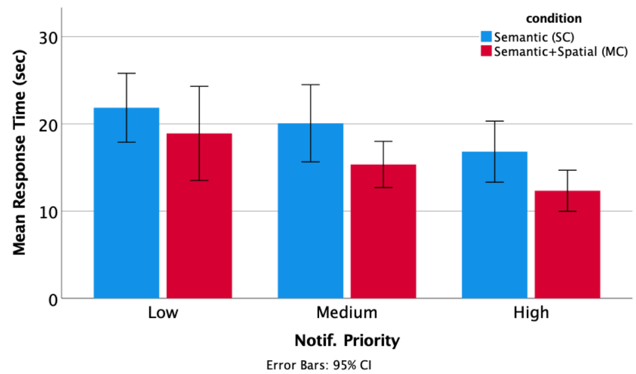

Figure 8: Mean response times in each condition, for each notification priority category.

As a final step, we examined whether there might exist interaction effects between the notification priority level and the experiment condition in terms of the response time, after controlling for the number of active notifications at the time of issue. The reason for this is that we can arguably assume that when many notifications are active in the users's environment, those with a lower priority would take longer than normal to be dismissed, as the user tends to other notifications first. In fact, a Spearman's correlation test shows that this assumption might be plausible, since there is good correlation between response time and number of active notifications at the time of issue ($\rho = 0.504, p < 0.001$). For this purpose, we employ a two-way ANCOVA analysis. We did not find a statistically significant interaction between notification priority and experiment condition, whilst controlling for active notifications, ($F_{2,1197} = 2.884, p = 0.056$, partial $\eta^2 = 0.005$), which can also be visually verified in Figure 9.

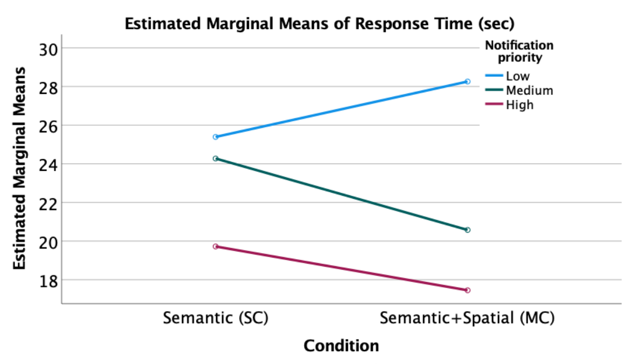

Figure 9: Results of interaction effects analysis between experiment conditions and notification priority.

Since we did not achieve statistical significance, we can examine the main effects of notification priority and experiment condition on response time, after controlling for the number of active notifications, using Bonferroni-adjusted post-hoc pairwise tests. From these results, it appears that experiment condition does not display a statistically significant effect ($\Delta_{\bar{x}} = 1.033, p = 0.406$). On the other hand, we observe statistically significant main effects of notification priority between Low and Medium ($\Delta_{\bar{x}} = 4.400, p = 0.006$), Low and High ($\Delta_{\bar{x}} = 8.238, p < 0.001$), and, Medium and Low ($\Delta_{\bar{x}} = 3.837, p = 0.039$).

4.6 Discussion

4.6.1 Overview of findings. In the preceding analysis, we found evidence to support *H1* (effect of spatial cue on response time). The addition of the 3D arrow was successful in guiding operators to the relevant instrument, reducing the response time to notifications. In a crowded information space, the need for visual search to locate instruments was reduced by the spatial cue, and this effect persisted even after several sessions had been completed, therefore adding further to the beneficial effects of familiarisation with the environment.

Next, we failed to find evidence that supports the hypothesis that response time is related to the angle between users' attention and the related instrument (*H2*), which means that navigation in the environment (body and head rotations) were quick enough and did not affect response time.

Finally, we found partial evidence to support our final hypothesis (*H3*) that the semantic cues relating to notification priority might reduce response time to important notifications. Although a trend towards reducing response time in higher-priority notifications was observed in both conditions, only the combination of semantic and spatial cues allowed participants to improve their response time in a statistically significant manner.

4.6.2 Implications. Overall these empirical findings demonstrate the viability and potential of replacing complex large-display type dashboards with immersive VR environments. Though we presented a marine vessel environment as the use-case for our work, the concept of complex, immersive VR control environments can be applied to a wide range of Industry 4.0 use-cases, for example, the monitoring of fixed industrial installations, such as electricity production and distribution installations, or dynamically configurable networks of manufacturing facilities (virtual factories). In fixed installations, the prototype could allow engineers to dynamically create customised views to monitor various system components, which could become as simple or as complex as might be required by the task at hand (e.g. simple monitoring of subsystems to responding to an emergency that affects or involves multiple interlinked subsystems). In the case of virtual, geographically distributed industrial systems (virtual factories), ad-hoc networked configurations of machines, installations and materials are created to serve the need to produce a particular product for a given customer under the constraints of prevalent conditions at the time of order. The complexity of the manufacturing configuration required to fulfil the order can vary significantly, therefore a dynamically adaptive monitoring environment can prove indispensable for such systems. In either case, however, the added flexibility afforded by the dynamically configurable immersive control room, means that engineers will continuously face the task of interaction with an unfamiliar setting. To overcome the problems associated with lack of familiarity with the environment, spatial cues can definitely play an important part, by assisting monitoring engineers to find the information they need quickly and accurately.

4.6.3 Limitations and future directions. Further research still needs to be carried out in order to investigate this promising concept more deeply, since our work has some obvious limitations. Firstly, the participants in our study were recruited through convenience sampling at our university, and therefore are not representative of the intended user-base for such a system. Since we focus primarily on issues relating to the fundamental effects of these spatial cues on users' cognition, the experimental findings are still useful, though for further development of the system, user requirements pertinent to the design and presentation of spatial cues and experimental evaluation should be carried out with a more representative sample. The task presented to the users is partially artificial, since the user does not really interact with the environment in order to solve particular issues. Implementing further controls and processes to solve problems (e.g. clicking on a sequence of switches to release superfluous pressure or to shutdown a system) will add to the cognitive load of operators, and it would be interesting to examine how processes can be supported in a VR environment whilst still maintaining situational and contextual awareness. We would also like to investigate the use of multimodal alerts, for example by providing spatial cues in 3D audio, which could guide an operator to a problematic component more subtly, especially for non-critical alerts.

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