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A Study on Improving Attention Redirection in Complex Systems Using Augmented Reality Cues

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Abstract

Attentional tunneling, a phenomenon where operators focus excessively on one task or channel of information while neglecting others, poses significant risks in critical, multitasking environments such as aviation, nuclear power, and cybersecurity. This study explores the use of Augmented Reality (AR) to mitigate attentional tunneling and enhance task performance by redirecting attention effectively across multiple visual cues. A user experiment involving eighteen participants was conducted to evaluate the effectiveness of two types of AR cues—Minimap and Line—compared to a control condition with no AR assistance. Participants performed a series of tasks using a head-mounted display (HMD) while interacting with a touchscreen in a simulated environment. Results show that both AR cues significantly reduced missed alerts and decreased cognitive workload, with the Line cue proving slightly more effective in reducing response time to peripheral alerts. The findings suggest that AR-based interventions can improve attention management and task performance in complex systems by countering the effects of attentional tunneling. This study highlights the potential of AR technology to enhance operational safety and efficiency in high-stakes environments.

CCS Concepts

• ***Human-centered computing*** → ***User studies; Mixed / augmented reality; Interaction design;***

1. Introduction

Operators in complex and high-risk environments, such as aviation, nuclear power plants, and cybersecurity centers, frequently face the challenge of managing multiple tasks simultaneously. In these settings, effectively allocating attention across various channels of information is crucial for maintaining safety and performance. However, a common cognitive phenomenon known as attentional tunneling, in which an individual's focus becomes excessively fixed on a single task or data source, to the detriment of other important information, poses a significant risk. Attentional tunneling has been implicated in numerous high-profile incidents and accidents, including aviation mishaps, traffic accidents, and cybersecurity breaches. It occurs when the cognitive load on an operator exceeds a manageable threshold, causing them to overlook critical signals that could indicate a need to switch tasks or reevaluate priorities.

Traditional methods for managing attentional tunneling have involved designing more intuitive interfaces, employing alarms or alerts, or developing training protocols to help operators manage their focus [WA09, PR97]. However, these solutions often have limitations. For instance, visual or auditory alarms can themselves become overwhelming or distracting, further complicating an operator's ability to allocate attention effectively. Moreover, these approaches often fail to provide dynamic real-time feedback that adapts to the evolving situational context, leading to suboptimal performance and missed critical information.

Recent advancements in Augmented Reality (AR) technology offer promising new avenues for addressing these challenges. Unlike static or non-interactive interfaces, AR can overlay digital information directly onto a user's view of the real world, creating a more seamless integration of critical data. This capacity allows for the real-time redirection of attention in a manner that is both context-sensitive and minimally invasive. AR has demonstrated potential in various applications, such as pilot training, surgical guidance, and emergency response, where maintaining situational awareness is critical [BJ09, LWWL18, LRB*11]. However, its specific role in counteracting attentional tunneling, particularly in multitasking environments, has not been thoroughly explored.

To bridge this gap, this paper presents a study that investigates the use of AR to manage attentional tunneling in complex multitasking environments. We focus on two distinct AR-based attention redirection methods—a Minimap cue and a Line cue—comparing them against a control condition. Eighteen participants engaged in a simulated multitasking scenario designed to induce attentional tunneling while their performance, alertness, and cognitive workload were measured. The objectives of this study are to assess the

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effectiveness of different AR cues in improving task management and reducing the risks associated with attentional tunneling, and to identify which type of AR intervention is most beneficial in these contexts.

The remainder of this paper is organized as follows: section 2 provides a review of related work, including the principles of attention management and the existing solutions for attentional tunneling. Section 3 describes the experimental setup, including the participants, apparatus, and procedures used in the study. Section 4 presents the results of the experiment, focusing on the impact of different AR cues on task performance and cognitive workload. In Section 5, we discuss the implications of the findings, comparing them with prior research and outlining potential applications. Section 6 concludes the paper by summarizing the main contributions of the study and suggesting directions for future research.

2. State of the art

2.1. Definition and principles of attention

Operators of complex and critical systems regularly face multi-tasking situations, where the management of attention may have extreme impact on the performance or even the survival of the system itself. Classical examples have been presented for years in the domain of aeronautics and aviation, but as well in the nuclear one, or more recently in cybersecurity [WM19, End00].

According to Wickens [Wic21], the concept of attention must be considered along two main dimensions. A first one is associated to the filtering of information and large numbers of stimuli and corresponds to the selective attention [WC21]. A second way to address attention is to consider it as a resource that can be shared between several tasks and lead to the concept of divided attention. Problems occur when one or several tasks to be handled by the operator only emit discrete and weak signals that should be detected to motivate task switching. Classic examples could be related to the detection of a pedestrian unexpectedly crossing the road or any kind of visual overheat alert on an engine (as mentioned in [Wic21]). Sharing attention between several tasks or between different areas of interest may be modeled with the SEEV (salience – expectancy – effort – value) model [WGH*17, ECdW18] so as to design better displays for complex systems or to understand operators' performance. In the case of divided attention, the operator can use a resource allocation policy and, for instance, decide to scan the different areas of interest with a controlled frequency to avoid any miss. But as discussed below, some problems arise when the task switching frequency is very low, leading to attentional tunneling which may provoke severe systems failures.

The concept of Perceptual Load Theory [Lav10, MGG16] is central to the study of selective attention. This theory asserts that the effectiveness of selective attention (the ability to remain undisturbed by distractors) depends on perceptual and cognitive load [LHFV04]. Globally, the prioritization and extraction of relevant elements in the field of vision is carried out by their visual salience ("Bottom-up" mechanism, extraction of eye-catching elements) and by selection according to metrics and patterns derived from memory ("Top-Down" mechanism). These two mechanisms coexist and can result in the deletion of visually salient information if it is not relevant or does not correspond to what is expected by the user's context [KKKH10]. These different elements are also to be found in the recent Guided Search 6 model [Wol20] which gives a systemic and pictorial vision of each stage in the visual search process.

More recent work has turned to neuroscience and proposed several markers [GSA20] to characterize the salience of a distractor and its effect on attention. The aim of the study is to determine the link between the nature of distractors and their processing in the pre-attentional, attentional and suppression phases, as evidenced by brain markers. The study's contribution to the definition of the most salient distractor, namely an "abrupt-on set distractor" acting in a bottom-up mode and as confirmed by a second study, independent of the task in hand [SOT08], is worth noting.

In summary, the main studies in the literature focus on eliminating distractors rather than taking them into account (with the notable exception of work on crisis alert management in cockpits and control rooms [CHB07]). Nevertheless, it is possible to use the general characteristics of the systems (perceptual load, cognitive load) and distractors usually used in studies to size and define prototypes and experimental protocols.

2.2. Definition of attention tunneling

As stated by Pedret [Ped23], "the persistent attempt to define attentional tunneling suggests that the research community has not arrived at a consensus definition for attentional tunneling".

We can however refer to a definition of reference provided by Wickens [WA09], while "defining the construct of attention tunneling as the allocation of attention to a particular channel of information, diagnostic hypothesis, or task goal, for a duration that is longer than optimal, given the expected cost of neglecting events on other channels, failing to consider other hypotheses, or failing to perform other task". Our research is based on this definition of attentional tunneling as recent works are using this concept to describe tunneling on virtual content only [SKG*21].

Attention tunneling has thus been proposed as an explanation of many aviation accidents [CMF96] and is regularly mentioned in driving accidents implying drivers "tunneled" on the phone instead of observing the traffic. This phenomenon can certainly be observed in various kinds of critical systems. As stated by Pedret [Ped23], "in high stakes examples, if a cybersecurity operator becomes attentionnally tunnelled on searching a high-risk area of a network while looking for threats, it is possible that other channels of information displaying important information do not get the attention they require". Therefore, it would be ideal to be able to maintain a state of focused attention as long as it is beneficial to the operator and task performance, but to be able to divert attention to another task when necessary to end a state of attentional tunneling.

2.3. Counter-measures to attention tunneling

Different approaches have been proposed to force or facilitate disengagement and break attention tunneling. One initial solution involved punctually removing information in the current area of interest: Dehais & al. [DTCR10] thus forced the operator's disengagement while erasing the information in the AOI, displaying a message in the blanked area for few seconds, and getting back to the normal display. As a continuation of these first attempts, a second approach was proposed in [SLID20] and consisted in applying a uniform semi-transparent red-orange mask on the display for 300 ms before going back to normal display. On both cases these quite intrusive interventions showed better detection of alarms, but also rose questions about the efficiency in time and level of performance on the main tasks in the system. Prinet [Pri16] proposed an alternative way in developing adaptive displays, distinguishing and comparing the effect of control and status augmentation on a modified MATB II simulator [SEMLCJ11]. This framework allowed to study the attention management in a multi-tasking environment (4 simultaneous tasks to manage, resource management, tracking, scheduling and system monitoring). The status intervention was designed to let the user know (s)he was allocating too much attention on one specific task of the simulation and took the form of a sequence of blinking red outline of the area of interest related to the task. The command intervention was intended to indicate the best task to proceed with and was displayed through a green outline around the related task to switch to. The main results of the experiment were that no effect was produced by the status intervention that even provoked a decrease in performance for some of the tasks. The command intervention led to an increase of performance for part of the tasks, but none of the interventions seemed to enlarge the attention focus enough to allow to detect peripheral alarms. This could be interpreted as keeping the focus of attention too narrow to deal with visual / attention tunneling. Lastly, others work focused on subtle gaze direction like [BMSG09] but they have proved to be efficient in contexts that are more complex than ours (our graphics are too simple to hide subtle cues inside).

2.4. Use of Augmented Reality for the management of attention

Most of research works related to the use of Augmented Reality for attention management have been focusing on two main aspects.

The first one is the attention funneling (this term expressing a mix of “attention tunneling” and “focus”) that allows to switch from a state of sustained attention (spending some resources on generic activity such as the assessment of a tactical situation, for instance) to selective attention more focused on a certain kind of event [YMWB03, BWC*21, HKA*18, Lam15]. As a positive effect of augmentation, superposing virtual / augmented hints on an image leads the operators to better focus on the related areas when necessary [WWR*23].

The second aspect is related to the bias that results from the augmentation of display with synthetic 3D representations and by extension with Augmented Reality devices. It was demonstrated that the use of HUD and augmented display facilitated the execution of the main task (especially in the domain of piloting [WAH*04]) but inhibited the detection of peripheral and unexpected events happening on the highways, for instance.

2.5. Research proposal

In this paper we aim at proposing AR based solutions to facilitate the redirection of attention toward multiple alerts that have meaningful impact on performance. The approach is relying on a multi-tasking paradigm and its definition refers directly to the SEEV model in the following sense:

- The main task (as described in details in the following paragraphs) consists in dealing with an intensive flow of "requests" emitted by a group of distributed but colocated agents. The density of request and related stress generates an attentional tunneling, which can be characterized by different variables including scores.
- A secondary task consists in acknowledging a set of alerts that are themselves distributed in the peripheral area of vision. Most solutions proposed in the past had been dealing with a single alert and could play with the whole area of display. In our case, the spatialization of the alerts themselves has to be taken into account in the assisting mechanisms.
- The primary task is focusing on the central part of a large screen as the alerts are displayed in the periphery, so that the eccentricity of stimuli is clearly raising extra difficulties in multi-tasking.
- The values (score points) respectively attached to the processing of "main targets" and the alerts have been balanced to compensate the respective frequency of appearance. The alerts are neither to be considered as distractors nor unexpected events, as it is often the case in previous experiments, but instead as included in a multi-tasking and task-switching paradigm.

Our approach is dedicated to the evaluation of the impact of using AR cues to facilitate the switching from one task to the other, and not to create a special focus on purpose. Among the cue possibilities, we chose to study two types of AR cues, one direct in the central vision (a line) and the other indirect and in the peripheral vision (a minimap).

- **Minimap Cue.** This cue serves as an overview tool, providing a small representation of the environment in the user’s peripheral vision. Positioned outside the immediate field of focus, the Minimap allows users to periodically check for active alerts, requiring them to interpret the indirect visual cues. This indirect approach is suitable for situations where it’s beneficial for users to maintain overall awareness while deciding when to switch their attention.
- **Line Cue.** This is a directive cue, providing direct, dynamic guidance to the exact location of an alert. Visible within the user’s central field of view, it directs attention immediately toward the active alert with a red line. As a colocated and prominent cue, the Line cue is designed to reduce cognitive effort by directly indicating the alert’s direction, ideal in scenarios where users need a strong, immediate prompt to reorient focus.

3. User Experiment

We conducted a user experiment to evaluate the effectiveness of attention redirection of different AR cues. One group of participants participated in this experiment and had to perform a perceptive task on a touchscreen; they had to align a slider with a random reference position several times during a Unity 3D session. Participants were wearing a HMD, and three different cues were displayed to help them execute an out-of-view task. The apparatus, procedure, and experimental design are successively presented in the following sections.

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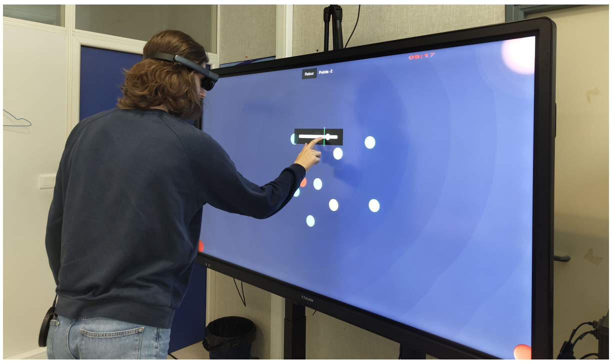

Figure 1: *Overview of the experimental setup with a participant completing a drone task while an alert is activated in the top-right corner of the touchscreen.*

3.1. Participants

The experiment involved eighteen participants (15 males, 3 females, mean age = 25.4, SD = 6.15, range = 22-49 years) with sixteen right-handed and two left-handed. All of them were working or studying in the university laboratory and were not aware of the experiment's purpose. They had normal or corrected vision with eight of them wearing glasses. Fifteen of them had already worn an HMD in the past.

This study was conducted in accordance with principles as stated in the declaration of Helsinki. The experiment was approved by the ethical committee of the host institution.

3.2. Apparatus

For this experiment, a Unity 3D prototype was designed and displayed on a large 75" CTouch touchscreen, as shown in Figure 1. For all the participants, the screen was at approximately 80 cm off the ground. Each participant was standing in front of the screen with the possibility of moving to the side and closer or further from it.

The prototype was built with Unity 3D version 2020.3.23f1 and was made as a drone swarm simulation where the goal is to complete tasks required by the drones in order to maximize a score, as shown in Figure 2. On the center of the screen, ten blue disks, the drones, are moving in random directions and at a constant speed. Sometimes, defined by a probability value of 1/20 at each second, a drone changes color to green and stop moving, immediately requiring an action from the participant. This action first requires the participant to press the drone, then it opens to the actual task. Multiple drones can be opened simultaneously, as there can be more than one activated at once. However, the participant cannot interact with multiple targets at the same time, since the prototype does not allow multitouch. Meanwhile, in the four corners of the screen, four red disks, called alerts, can activate, one at a time, for a given activation probability of 1/20 at each second. An alert activation is defined by a small light halo on an alert. These alerts are immobile. A simple press on the alerts deactivated them. The drones need their task to be achieved under fifteen seconds after their activation, and the alerts, under five seconds. When the time is up, the task is supposed to be missed. The remaining time for each drone can be guessed by the color of the disk, which allows priority visualization such as what was used in [OLKK19]. The drone turns green at its activation, then yellow at 7 seconds, and finally red at 11 seconds. The drone task is a simple slider to align with a random target. A feedback, green or red, is displayed for 0.5 seconds. In order to get points, the participants have to complete the drone tasks before their due times. Each missed task, drones' and alerts', is removing points. Missing an alarm removes 5 points and its processing does not give any points. While the drone task is removing or allowing 1 point. The points earned are dynamically displayed on the background, in green or red, and the total score is always displayed at the top of the screen for the user's convenience.

Three attention redirection conditions were tested: two types of AR cues, a minimap and a line, and one type of no AR, a control condition where nothing was displayed (see Figure 3). The Minimap cue is a small replicate of the game placed in AR on the right of the participant's visual field. It was a simple rectangle with 4 red dots at its corner, when a corner changed color to white, an alert was active at the corresponding corner in the actual game. This cue is located in the peripheral vision and can be considered as an indirect help because it requires the user to make a cognitive effort to deduce in which corner the alert is activated. The line cue is a red line presented at the center of the visual field and directed to the corner where an alert is active, the line updates its position at each game frame. This cue can be considered as a colocated and direct help since the line is conducting directly to the activated alert. The minimap was always displayed whereas the line was only showing when an alert was activated. The HMD used for this experiment was the Magic Leap 2, with a $45° \times 55°$ FoV and a resolution of 1440×1760. No eye-tracking data was collected. Participants had to wear the HMD the whole time of the experiment even when no AR cues were projected. In this way, the same HMD dimming was used for the three conditions and the visual field range was constant. The AR scene was built under Unity 3D version 2022.2.20f1. At the beginning of each condition, a calibration was needed to match the position of the AR cues with the alerts' positions. Five markers on the screen had to be tracked, corresponding to the corners and the center. When tracked, a white cube was displayed in the AR scene at the position of the marker. When the five cubes overlapped their corresponding markers, the calibration was manually completed.

3.3. Task and procedure

Each participant started by reading and signing a consent form containing information on the experiment. After filling a pre-questionnaire, they were given some explanations on the task and were allowed a 2-minute training without the HMD, to get used to the touchscreen and prototype. Then, three conditions, each composed of a calibration procedure, followed by 10 minutes of playtime and a NASA TLX questionnaire, were completed in a user-specific order. The participant was allowed a small break between each condition.

During a condition, a participant had approximately 218.74 (SD = 13.36) drone tasks to process and 102.85 (SD = 27.78) alert tasks. The activation of the different objects was not scripted but was all probability, therefore participants did not have the same event pattern. The participants were instructed to maximize their score and therefore to minimized the number of missed alerts and drones.

To avoid order bias, each participant had a random condition order, one for each attention redirection method. With three conditions, 18 participants was enough to have three subjects for each of the six combinations.

The total time of the experiment was 1 hour on average, including instructions, pre-questionnaire, training, three conditions with their questionnaires, and debriefing. The AR display was worn for a maximum of 45 minutes.

3.4. Experimental design

The screen size is large enough to put the alerts out of the center field of vision and the drone movement is limited to a central zone representing 24% of the whole screen. The purpose of this setup is to force the user to process the main task (the drone one) while putting them in a consistent workload and recreating an attention tunneling.

The two AR cues used are different kinds of help, the Minimap is a passive redirection. The participant had to look at it to see it and get information on the activated alerts. On the other hand, the line is a more active help. It is always in the visual field of the user and cannot be ignored.

The design model only contains one independent variable: the attention redirection method used (None, Minimap, Line). Each participant has experimented the three conditions.

3.5. Research questions

The purpose of this experiment was to study if AR cues are efficient enough to counter the attention tunneling effect and, if this is the case, then evaluate which AR cue is the best among passive or active help.

Considering this, our main research hypotheses were the following:

- **H1**: The number of missed alerts is larger when no redirection cue is displayed.
- **H2**: The participant workload is lower with AR cues.
- **H3**: The task process time improves with AR cues.

3.6. Statistical analysis

A Friedman test was used to analyze the results since the data did not pass the parametric test requirements. Each tested group corresponded to one of the attention redirection methods tested: one for the line, one for the map, and one for the no AR method. The purpose is to see if one of the groups is significantly different from the others. Since all game events were randomized, the percentage of missed drones or alerts was a more accurate data than the total number of missed drones or alerts. The analyzed data also contains the NASA TLX scores and the average process time needed to complete a drone or an alert task.

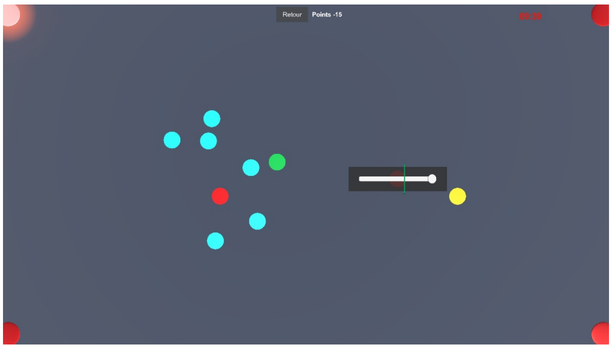

Figure 2: *The Unity 3D prototype used in the experiment. Here, the top-left alert is activated and three drones are requiring an action, one red, one yellow and one green. One drone has been pressed by the user and has its slider open and waiting for process. The remaining time is displayed in the top-right, the current score is displayed on the top-middle, next to a return button to exit the current condition.*

4. Results

On average, 28.11% of the alerts were missed during the no AR condition whereas only 11.97% and 9.82% were missed for the Minimap and Line condition respectively. The percentage of missed drones is slightly the same for the three conditions: 15.88% (Line), 15.87% (Minimap), and 18.73% (no AR), as shown in Figure 4. The Friedman test showed a significant difference between the cues for the percentage of missed alerts, ($\chi^2(2) = 21.777$, $p < 0.001$). On the contrary, no significant effect was seen for the percentage of missed drones ($\chi^2(2) = 3.296$, $p = 0.192$). Following a Conover posthoc test, for the missed alerts, we get a significant effect between the two AR conditions and the no AR one (NoAr - MiniMap: $p < 0.001$; NoAr - Line: $p < 0.001$) but no difference was found between the two AR cues (Line - Minimap: $p = 0.31$). These results show that the AR cues are efficient to redirect the user attention on the alerts. The non significant result for the missing drones can be explained as there is no redirection on the drones since they are always in the center of the visual field.

For the NASA TLX dimensions scores, the Friedman test was found relevant for five dimensions out of six (see Figure 5). Only the performance dimension had a p-value greater than 0.05 ($\chi^2(2) = 2.179$, $p = 0.336$). In comparison to the Conover posthoc test, the differences in dimension scores are also significant between the two AR cues and the non-AR condition for the effort (NoAr - MiniMap: $p < 0.01$; NoAR - Line: $p < 0.001$; Map - Line: $p = 0.154$) and frustration (NoAr - MiniMap: $p < 0.001$; NoAR - Line: $p < 0.001$; Map - Line: $p = 0.483$) About the mental demand, the line cues result is significantly lower than the NoAR condition and the MiniMap condition (NoAr - MiniMap: $p = 0.074$; NoAR - Line: $p < 0.001$; Map - Line: $p < 0.05$). Also, for the physical (NoAr - MiniMap: $p = 0.115$; NoAR - Line: $p < 0.05$; Map - Line: $p = 0.207$) and temporal demands (NoAr - MiniMap: $p = 0.115$; NoAR - Line: $p < 0.05$; Map - Line: $p = 0.224$), the line cue is once again slightly differentiable with the no AR condition result.

On average, the processing time needed to complete a drone task

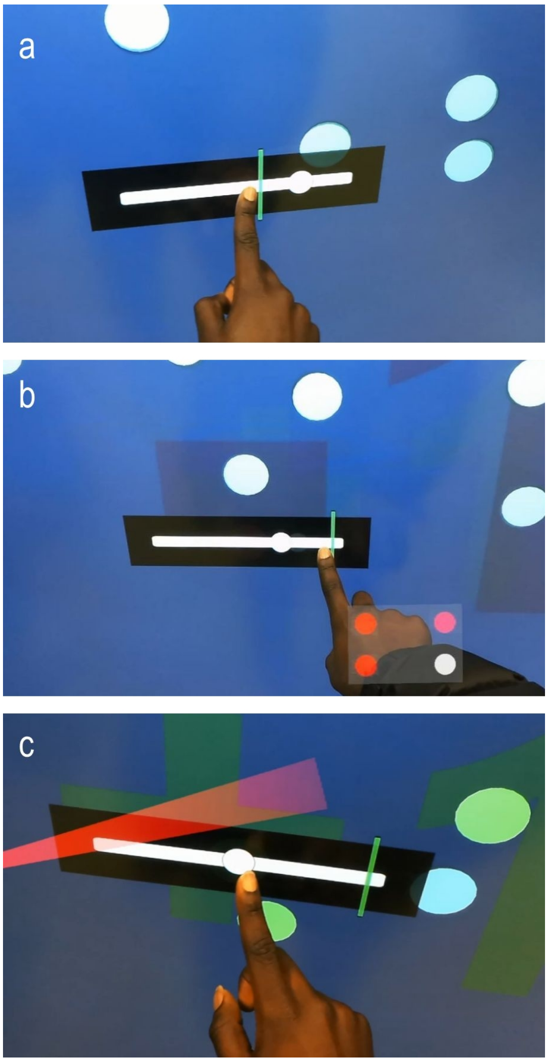

Figure 3: *(a) The NoAR condition where nothing is displayed. (b) The MiniMap condition displayed on the bottom right. Here the bottom-right alert is activated. (c) The Line condition with a red line displayed and directed to the activated alert, here the bottom-left one.*

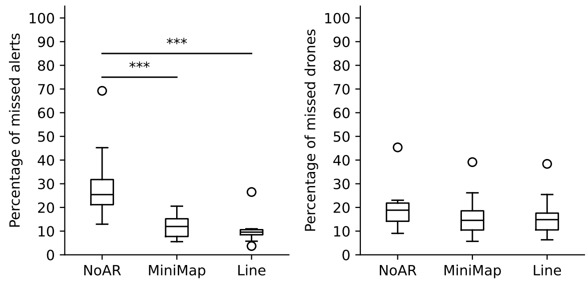

Figure 4: *Percentage of missed alerts and drones. '***' indicates significant difference with $p < 0.001$.*

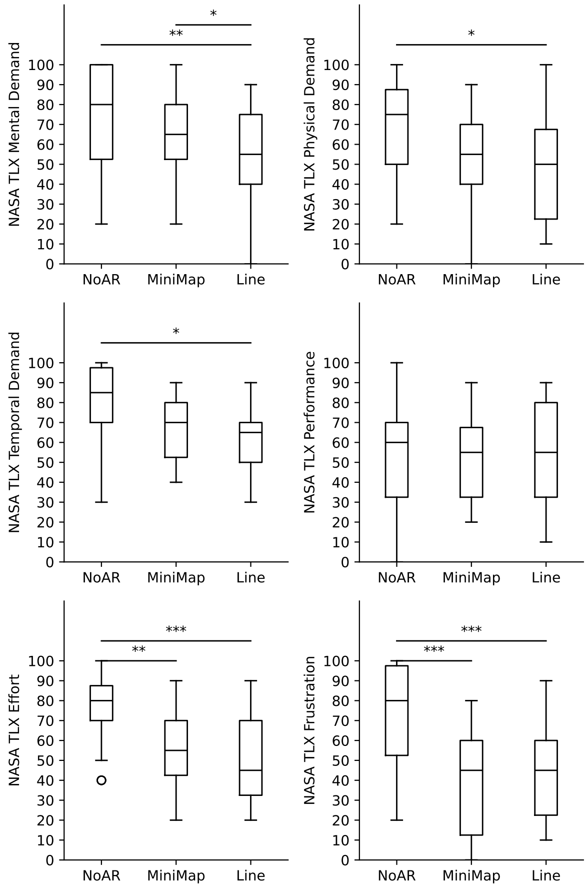

Figure 5: *The NASA TLX dimensions (from top to bottom and left to right): mental demand, physical demand, temporal demand, performance, effort and frustration. '*' indicates significant difference with $p < 0.05$. '**' indicates significant difference with $p < 0.01$. '***' indicates significant difference with $p < 0.001$.*

was about 7.16s, for the Line condition, 7.15s, for the MiniMap condition, and 7.71s for the no AR condition. For the alert process time, there is on average, 2.51s, for the Line condition, 2.71s, for the MiniMap condition, and 3.45s for the NoAr condition, as shown in Figure 6. The Friedman test results are significant for the alert process time ($\chi^2(2) = 27.086$, $p < 0.001$) whereas this is not the case for the drone one ($\chi^2(2) = 5.444$, $p = 0.066$). The Conover post-hoc test for the alert process time is significant for every pair of modes (NoAr - MiniMap: $p < 0.001$; NoAr - Line: $p < 0.001$; Map - Line: $p = 0.0054$).

5. Discussion

5.1. Evaluation of Hypotheses

Taken together, our results show that AR augmentations provide significant help to the user and improve their performance. In particular, they allow for a significant reduction of the number of missed alerts which validates H1. The number of drones missed

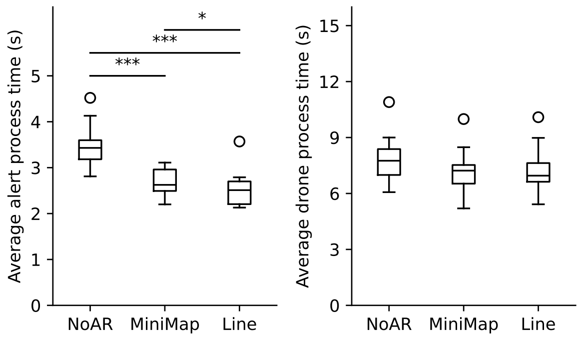

Figure 6: *Average process time for drone's and alert's task. '***' indicates significant difference with $p < 0.001$. '*' indicates significant difference with $p < 0.05$.*

did not vary significantly between the different conditions, which shows that in this experiment the better handling of the secondary task did not impact the primary task. These results underline the potential use of AR to prevent attention tunneling and improve the efficiency of systems involving several tasks.

Regarding H2, most of the NASA TLX dimensions scores decreased when using the AR augmentations for the task, especially the mental demand and the effort dimensions. This implies a lower workload demand when the participants were assisted by an AR augmentations. This result validates our hypothesis H2 and shows that, if carefully designed, AR augmentations can assist the user and reduce their cognitive load.

Finally, results showed that the average process time for the alerts decreased when using AR augmentations while the average process time for the drones remained constant across the conditions. This validates H3 and shows that AR augmentations improve the task speed on top of the task performance.

5.2. AR augmentations and attention tunneling

As presented in section 2.2, the definition and as such detection of an attention tunnel is still hard to assess. However, our experiment shows that AR was able to provide an efficient tool to allow an operator to better manage a complex task involving several subtasks of different complexity and locations.

Moreover, we chose two different kinds of augmentations, one being situated but not directly related to the viewed real element (Minimap) while the other was colocated and provided a direction that could even be interpreted as an order (Line). The average process time of the alerts was lower in the Line condition than in the Minimap condition and most of our results showed a trend toward a better efficiency for the Line compared to the Minimap. This suggests that a direct, clear and colocalized order could be the best way to mitigate attention tunneling when dealing with simple secondary task. Contrary to some other studies [Pri16] the colocalized and as such anchored in the primary center of focus of the AR element could be a key factor of its efficiency. In high-stakes environments such as aviation and healthcare, these AR cues could support operators by enhancing situational awareness and reducing the risk of missing critical information. Directive cues like the Line, which provide immediate visual guidance, would be ideal for urgent, time-sensitive tasks—such as alerting a surgeon to a critical change in patient vitals or guiding a pilot to rapidly identify a system alert. Conversely, overview cues like the Minimap would be better suited for maintaining broader situational awareness, allowing users such as air traffic controllers or operating room staff to monitor multiple information streams without being overly disrupted, thus balancing focused attention with ongoing environmental awareness.

5.3. Limitations and Future Work

While our study provides valuable insights, it also has several limitations. First, the sample size was relatively small (18 participants), which may limit the generalizability of the findings. Future studies should involve larger, more diverse participant groups to confirm the results. Second, the experiment was conducted in a controlled laboratory environment, which may not fully replicate the complexity and stress of real-world multitasking scenarios. Future research should aim to explore the effectiveness of AR interventions in more realistic and cognitively demanding settings that closely mirror the complexities encountered in real-world environments. Last, the randomization of events used during the experiment could have created some bias in the user performance evaluation, especially for the NASA TLX results, since they didn't all encounter the same challenges during the simulation.

Furthermore, our study did not consider the potential long-term effects of using AR cues, such as user fatigue, adaptation, or overreliance on augmented guidance. Future research should investigate these factors to understand how the benefits of AR can be sustained over time without unintended consequences. It would also be valuable to explore different types of AR cues and configurations, as well as their impact on different types of tasks and environments, to determine the most effective strategies for various use cases.

6. Conclusion

This study investigated the use of Augmented Reality (AR) to counteract attentional tunneling in multitasking environments. By comparing two distinct AR-based attention redirection methods, a passive Minimap cue and an active Line cue, against a control condition with no AR support, we aimed to assess the effectiveness of AR interventions in improving task management, reducing missed alerts, and lowering cognitive workload.

Our findings indicate that AR cues can significantly mitigate the effects of attentional tunneling, particularly in scenarios where operators must manage multiple tasks simultaneously. Both AR methods tested in this study, the Minimap and the Line, were effective in reducing the number of missed alerts and decreasing cognitive workload, as evidenced by the NASA TLX scores. However, the active Line cue, which remained in the user's central visual field and provided dynamic, direct guidance to the location of alerts, demonstrated a slight edge over the Minimap in terms of performance improvement, particularly in reducing the time required to process peripheral alerts. This suggests that the effectiveness of AR cues in managing attention depends not only on their presence but also on their design characteristics, such as visibility, immediacy, and spatial integration with the user's task environment.

In conclusion, this study contributes to the growing body of knowledge on the use of AR for attention management in critical environments. It demonstrates that AR has the potential to significantly improve multitasking performance by mitigating attentional tunneling, reducing cognitive workload, and facilitating faster response times to critical alerts. As AR technology continues to evolve, its application in high-stakes domains offers promising opportunities to enhance safety, efficiency, and decision-making. Moving forward, a deeper understanding of how to optimize AR cues for different operational contexts will be essential to harness its full potential in real-world scenarios.

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