THESIS

EFFECTS OF HEAD MOUNTED DISPLAY CLUTTER, TRANSPARENCY, AND OPTICAL DISTANCE ON HUMAN PERFORMANCE DURING NAUTICAL NAVIGATION

Submitted by

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ABSTRACT

EFFECTS OF HEAD MOUNTED DISPLAY CLUTTER, TRANSPARENCY, AND OPTICAL DISTANCE ON HUMAN PERFORMANCE DURING NAUTICAL NAVIGATION

Head Mounted Displays (HMDs) are increasingly proposed as a solution designed to reduce costly visual scanning in transportation systems such as cars, planes, and boats. The advantages of HMD platforms are obvious and intuitive. Operators can maintain "eyes out" on the scene in front, to avoid hazards and obstacles, while still processing and monitoring critical display information related to navigation and vehicle operations, as well as communication displays, notifications, and chat boxes, with reduced visual scanning between the display and the world beyond. However, HMD interface clutter, transparency, and optical depth are crucial factors that may impair human performance. This thesis explores the impact of these three HMD interface parameters in nautical navigation tasks. 54 participants across two experiments performed a realistic nautical navigation task in a virtual environment with obstacles, navigating a small speedboat while observing navigational information via an HMD interface. The display interface was varied according to three factors: the amount of information shown (HMD clutter), the optical distance of the information from the user's eye (2 meters vs. 10 meters), and two opacity settings (low and high), which adjusted the trade-off between the clarity of virtual elements on the display and the visibility of the real-world scene viewed through the HMD. Environmental clutter was manipulated by varying the number of low-salient objects that pose navigational hazards, including mines, wooden boxes, planks, barrels, and logs, as well as other objects that present navigation challenges. Participants were evaluated on task completion time, distance traveled to reach the endpoint, proximity to obstacles, and mental demand. Results showed that participants completed the task more quickly when the number of islands increased, particularly in transparent displays. They also performed the task with shorter distances when the display was positioned at a near optical distance and was

highly cluttered. Hazard proximity increased as the number of islands in the environment grew while navigating highly cluttered scenes, especially in opaque displays. Increased proximity to hazards occurred in two ways: when the display was opaque and highly cluttered, and highly clutter environment and near optical distance display. Mental demand followed the same pattern as completion time. This provides a foundation on which more work can ask more complex questions about these relationships and their impact on navigational efficiency.

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DEDICATION

I would like to dedicate this thesis to my immediate family, Roman and Mikah Cardenas, and Elena Chavez - who have never given up on me. I will always keep going because of you.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

Introduction[1]

1.1 Head Mounted Displays

Head Mounted Displays (HMDs) are increasingly proposed as a solution designed to reduce costly visual scanning in transportation systems such as cars [1,2], planes [3–9] and boats [10,11]. The advantages of HMD platforms are obvious and intuitive. Operators can maintain "eyes out" on the scene in front, to avoid hazards and obstacles, while still processing and monitoring critical display information related to navigation and vehicle operations, as well as communication displays, notifications, and chat boxes, with reduced visual scanning between the display and the world beyond. The non-HMD alternative, such as a tablet or head-down instrument panel, imposes frequent scanning of the vehicle's instruments to perform relevant tasks, while taking visual attention away from monitoring for hazards in the path of travel. Such scanning will increase fatigue and leave the operator vulnerable to missing important items in the forward scene when the eyes are "head down" [12].

1.2 HMD Applications

HMDs have the ability to aid operators in a variety of tasks by giving them additional information. The way that HMD can be used vary across fields like education, navigation, military and more. Some specific examples of this usage are:

Education: HMDs can transform traditional education material and provide immersive and interactive learning experiences. In Computer Science (CS) education, these devices have been used to teach high level concepts such as finite state machines by representing the information in a game format [13]. In the medical and health education, HMDs have been used

[1]Damyenn R. Cardenas, Chirag Rajubhai Kandoi, Christopher Wickens, Mohammed Safayet Arefin. Effects of Environmental Clutter, Head Mounted Display Clutter, and Head Mounted Display Transparency on Human Efficiency, Safety, and Mental Demand During Navigation. Human Factors.

to train nurses by creating virtual operating rooms that provide a simulated surgical procedure [13].

Medical Field: As mentioned above, HMDs have been used to train medical staff but they have also been used in treatments. HMDs have been used in treatments of irrational fears and phobias as they provide believable simulations [14]. HMDs can also be utilized by render charts such as MRI, CT and ultrasound scans into the surgical space aiding in minimizing invasive surgeries [15, 16].

Manufacturing & Maintenance: In handling and assembly tasks, HMDs can provide virtual assembly sequences that can help workers get better at actual assembly of parts [14]. For maintainers, they can use HMDs to establish remote connection with an expert; allowing experts to guide maintainers through the repair and view virtual models of the real objects [17].

1.3 HMD Clutter

Clutter effects with HMDs can be categorized into two components: overlay clutter and scene clutter. Display clutter refers to the near domain information, the information provided by the HMD. Scene clutter refers to the physical surroundings of an operator and how much information it contains. Regardless of the category, clutter fundamentally complicates the processing of information presented in either domain, as the visual complexity increases when two or more sources of information are placed onto the same region [18].

Importantly, clutter can be computationally computed [19–22]. From basic visual attention science is derived the feature congestion model of clutter [19]. This model in turn is derived from Treisman's Feature Integration Theory [23], which describes the characteristics of individual items and a target search field that impose a slower serial search inspection of all items in a search field to assess target identity. Hence, the model will penalize scenes that contain items with multiple heterogeneous feature dimensions in close spatial proximity. Feature congestion is readily applied across naturalistic search scenes. A second, computationally simpler clutter metric that can be applied to synthetic displays and to less complex scenes is the object-count model and metric [20–22]. This is based upon Sternberg's serial self-terminating visual search model and its subsequent incorporation into Wolfe's [24] Guided search model. Here, visual search time is penalized by a fixed amount for each additional non-target element that appears in the search field, whether a display item or a discrete object in the scene beyond.

1.4 HMD Transparency

One design strategy to mitigate the impact of clutter is to vary the transparency of the HMD display. Display transparency or, its converse, opacity [9,25,26] aims to achieve a balance between the clarity or legibility of information presented on the display and the visibility of real-world scenes viewed through the HMD. Increasing display transparency should mitigate search of the scene to the extent that the increment in transparency will (a) eliminate the possibility of total occlusion of critical items in the scene and (b) create an added pre-attentive feature (intensity) that can discriminate the two overlaid domains (scene, display), and hence ease the search of each [8]. However, increasing symbology transparency can reduce its legibility in a manner predicted by basic visual contrast functions [27], which will disrupt not only the visual search of the display, but also any display-related task that requires perceptual interpretation, such as reading text or visual symbols.

Logically, if the display interface is entirely opaque (unable to be seen through), perception of far domain information is impossible, and performance on a task requiring scene information, such as hazard detection and avoidance, will be null. If only the imagery on the display is opaque, then these displays superimpose themselves on the far domain and create "walls" of occlusion that inhibit the ability to see the scene behind them without head movement, and the area of such walls will be directly proportional to the amount of display clutter. If the display interface has high, but not perfect transparency, performance based on scene information will be high, and only degraded to the extent that there is significant display clutter. However, performance on display-related tasks, such as map consultation, will be degraded to the extent that scene clutter is high [21].

Furthermore, as the display information is less opaque (more transparent) and scene clutter is high, display legibility and readability deteriorate.

1.5 HMD Optical Distance

In standard viewing conditions, the visual angle of an object decreases as the distance from the observer increases; this change in visual angle serves as a powerful depth cue known as relative size [28]. In depth perception, this cue is useful in helping observers report accurate distance estimates [29]. In HMDs, this relationship between distance and visual angle is often manipulated to help information remain readable; if the visual angle is subtended by a display, it can begin to affect the visual acuity of the symbols and texts in the display [30]. Typically, to ensure information remains legible, designers scale the virtual text to maintain a constant visual angle [28, 31].

Not only do display designers need to keep the visual angle in mind, but they must also consider human physiology. Warden et al. [22] discuss the biological mechanism of peripersonal space, which is a tendency for humans to prioritize information perceived as closer to oneself. Arefin et al. [28] looked at focal distance switching, which refers to how the eyes' lenses change to accommodate new focal distances. The time it takes for the eye lens to adjust to this new focal distance is called transient focal blur, and it takes 425 milliseconds for the image to return to sharp focus. Both of these biological mechanisms can cause information in the display to be missed due to lack of focus.

1.6 Problem Statement

Despite the advantages, there is one major cost to positioning information superimposed on the forward field of view, whether in a HUD or an HMD, and this is referred to as overlay clutter [18, 22, 32]. This negative effect (increased response time, decreased accuracy, and others) may be caused by elements either on the display (display clutter) or in the scene beyond (scene clutter), disrupting perception of elements in the other domain (scene or display, respectively). In aviation, it has been found that the overlay clutter of HUDs for landing guidance can disrupt the detection of small visual-angle hazards, such as runway incursions [33, 34].

Relatively few studies appear to have examined both scene clutter and display clutter, and both have been shown to have a roughly linear degrading effect on performance as clutter increases [21,22]. None appears to have examined both sources of clutter in conjunction with display transparency. In applications, the importance of quantifying HUD or HMD clutter is to provide design guidance that constrains the amount or type of display information presented while the vehicle is in motion.

The detrimental effects of overlay clutter are well known, but they can be mitigated by reducing clutter and adjusting opacity (transparency) to some optimal level. However, prior research has not examined the tradeoff between these two variables in realistic navigation tasks, particularly within the nautical domain. In the current experiment, we do this within a VR paradigm in which participants navigate a small speedboat through a littoral environment populated by small islands and floating hazards of varied density (environmental scene clutter), while necessary navigational information is presented on a simulated HMD in a minimap, whose display clutter and opacity levels are manipulated as experimental variables.

1.7 Research Goals

This study offers new insight by investigating the relationships among display clutter, display opacity, display optical distance, and environmental clutter in real-world nautical navigation tasks. To our knowledge, these experiments are the first to examine the effects of overlay and scene clutter on opacity and optical distance in nautical navigation tasks. The exploratory research questions are as follows.

RQ1: To what extent is nautical navigational performance impacted by environmental clutter and display parameters such as display clutter, display opacity, and display optical distance?

RQ2: To what extent is nautical navigational safety impacted by environmental clutter and display parameters such as display clutter, display opacity, and display optical distance?

Exploring these questions will help provide a foundational understanding of these relationships and what future work is still needed to investigate before system designers can create guidelines of how to best present information in HMDs. These questions are addressed in chapters 3 and 4.

1.8 Journal Paper

I would like to acknowledge that a significant portion of this thesis is reused from the journal paper I published with my coauthors to Human Factors [35].

Chapter 2

Related Works[2]

2.1 Types of Display

Head Down Displays (HDDs) are visual displays that are separate from the operator's line of sight and in transportation systems they are typically physically part of the vehicle such as center consoles in cars or are portable devices such as tablets. HDDs are unique compared to HUDs and HMDs as they do not occlude the far domain, the location of HDDs require operators to avert their gaze from the far domain (real world environment) to access information in the near domain (additional information like vehicle instruments or maps) [36].

Head Up Displays (HUDs) are a type of visual display that superimposes imagery over the operator's FOV. HUDs are similar to HMDs but are typically mounted to the vehicle [30] allowing for operators to view near domain information and the far domain simultaneously. This creates a restriction to the HUD as they are designed so that legibility of the near domain is specific to the operator's viewing positions, also know as the "eye box" –a three-dimensional region where the information can be viewed by at least one eye. [30].

Head Mounted Displays are a way to superimpose virtual information onto the real world and is commonly done via augmented reality (AR). Augmented reality is a visual process of displaying virtual information and objects in the real world and is often defined by the combination of real and virtual images in real time [15]. AR HMDs can overlay near imagery over the far domain and are an alterative to traditional Head Up Displays or Head Down Displays. HMDs are physically attached to a operator's head by a helmet or headset, which allows for near imagery to be in close proximity with the far domain providing benefits to human performance by keeping the near domain and far domains within the same field of view [37].

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[2]Damyenn R. Cardenas, Chirag Rajubhai Kandoi, Christopher Wickens, Mohammed Safayet Arefin. Effects of Environmental Clutter, Head Mounted Display Clutter, and Head Mounted Display Transparency on Human Efficiency, Safety, and Mental Demand During Navigation. Human Factors.

The clear empirical performance advantage of superimposed imagery, such as the HMD, has been shown in extensive research on vehicle-mounted HUDs [38] and HMDs [39], and it also lowers the mental workload of processing information by moving visual information closer to the driver's field of view (FOV) [40].

2.2 Clutter

A large majority of research regarding HMD clutter have looked at measuring and creating computational models of clutter [19, 21, 41]. Many other studies have looked at attention mechanisms in cluttered environments such as scan-clutter trade-off [42] and attentional tunneling [38, 43–45].

Previous studies looked to apply and understand the effects of clutter but few have aimed to examine both overlay clutter and scene clutter. Viertler et al. [46] analyzed the effects of visual clutter on mental demands and occlusions of HMD display overlays in 3D-conformal rotorcraft HMDs. Participants in a rotorcraft simulation environment had to manage stabilization and navigated using HMDs presenting terrain and obstacles. Their finding was information blending, which can help ensure HMD content does not mask important real-world features by changing HMD features to have semi-transparent backgrounds and continuous fade-out (become more transparent). Duan et al [47] investigated the "interaction effect between background and AR contents." They found that superimposing the two layers (real-world scene and AR display) causes visual confusion which altered how humans were able to perceptive either domain (background and AR contents) and needs to be understood to improve quality of experience. Warden et al. [22] study compared clutter cost of HMDs in a real-world scene to the cost of visually scanning when the information is presented separately. Participants performed focused attention task in military scenarios, by conducting a visual search task on the scene or display. They found that far domain clutter suppressed the readability of near domain information and vice versa in what they define as clutter directionality.

Based on our knowledge, prior research has not examined both types of clutter in a realistic nautical navigation task.

2.3 Transparency

Variations in the opacity or transparency of the HMD interface have been investigated very little. To our knowledge, only a few previous studies have explored altering the transparency of virtual interfaces to enhance user visibility. Jing et al. [48] investigated HMD interface opacity in the context of subway maintenance tasks, suggesting that increased transparency might pose safety risks by complicating worker navigation. Hussain & Park [25], using a visual search task, concluded that transparency levels between 50% and 75% were optimal. Wong [26] investigated how transparency affects multi-layered displays in command and control scenarios, finding that while increasing transparency initially lengthened reading times, a transparency level of 70% restored performance to parity with fully opaque displays. However, their sample size (N = 6) was extremely small. These outcomes suggest a complex, non-linear relationship between transparency and readability, cautioning that the improper application of transparency can hinder perception, amplify distractions, and compromise legibility. Winterbottom et al. [9] review some issues of HMD transparency in aviation, but most of their focus is on monocular HMDs. None of these studies addressed varying levels of HMD clutter and how these might trade off against transparency, nor did they incorporate real-world navigation scenarios. The potential interactions between opacity and clutter in their effects on attention-mediated task performance are of both theoretical and practical significance.

To the best of the author's knowledge, our study is the first to examine clutter effects on transparent and opaque displays in a nautical navigation task.

2.4 Optical Distance

Optical distance research typically examines the distance of HMD overlays in two ways: the optical distance at which content is rendered and the spatial separation between displays. Masnadi et al. [49] had participants perform a blink walking task in three levels of virtual environment clutter, where they changed the distance of the target (3m, 4.5m, 6m) they would walk to. They found that increased environmental clutter reduced the tendency to underestimate distance. Flittner [50] looked to inquiry if visual clutter analysis of a single plane AR UI can be expanded to multi-plane AR UI. Participants perform a visual search task for a target image within the 2D AR array at three different distance of 2m, 4m and 6m. What they found was that targets in the 4m and 6m depths had longer visual search times compared to the 2m distance, which the author attributed to distance switching of the different apparent distances. Imamov et al. [51] study looked at glanceable interface positions by having participants perform a primary task which required switching focus to a glanceable virtual table at 1m, 2m and 3m from the participant at various positions. The study found that displaying the virtual table further from the central task position increased context switching time and discomfort. They also found that participants completed the task faster when the table was rendered at 3m, making it closer to the primary task depth of 4m.

To the best of the author's knowledge, our study is the first to examine clutter effects on optical distance in a nautical navigation task.

Chapter 3

Experiment 1[3]

In this experiment, we examine the joint effects of clutter, either displayed items on the HMD (display clutter), or a scene filled with many objects viewed through and beyond the HMD interface (scene clutter), and display transparency, the ability to see through scene or environment items through the HMD interface information, in a realistic nautical navigational task. In the following chapter detail is given about the methods, variables, experimental setup and virtual environment that was used to accomplish these goals.

We hypothesize that:

1. Navigational efficiency will be:

- **1a** decreased by increases in environmental clutter (longer transit time), because of the increased complexity of the environment.
- **1b** increased by an increase in display opacity, which will render the minimap, useful for route planning, more legible.
- **1c** decreased by display clutter as more elements on the display may retard the visual access of the elements relevant to efficient navigation, particularly the minimap and time clock

2. Hazard collisions or near collisions, compromising safety, will be:

- **2a** increased by environmental clutter, as there are more opportunities for penetration of safety-boundaries around islands and floating objects as islands become more frequent.
- **2b** increased by increasing display clutter, as all environmental objects will be more obscured by semi-transparent elements on the display.

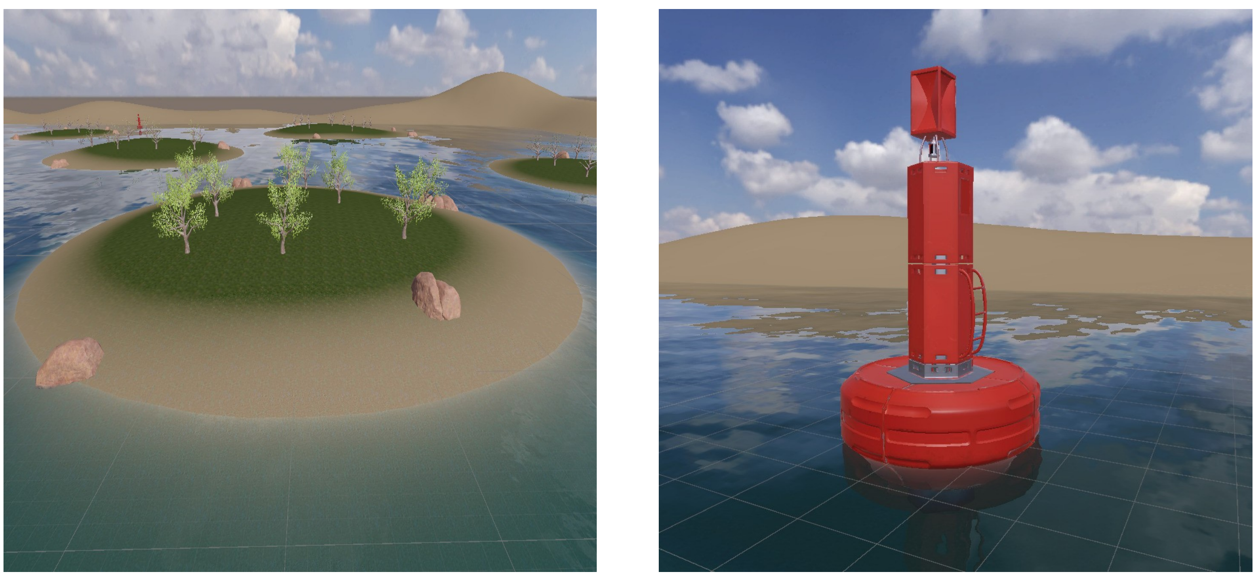
[3]Damyenn R. Cardenas, Chirag Rajubhai Kandoi, Christopher Wickens, Mohammed Safayet Arefin. Effects of Environmental Clutter, Head Mounted Display Clutter, and Head Mounted Display Transparency on Human Efficiency, Safety, and Mental Demand During Navigation. Human Factors.

2c increased by increasing display opacity (decreasing transparency) as all items in the scene (hazards) will be more obscured.

In hypothesizing these main effects, in a 2x2x2 factorial design, we anticipate that some interactions between variables may also be observed, but we are not sufficiently confident to predict the direction of these interactions in advance: for example, whether transparency will amplify or diminish the detrimental effects of either type of clutter.

3.1 Apparatus and Setup

3.1.1 Virtual Environment and Task



(a) **(b)**

Figure 3.1: (a) Island terrain and environmental texturing; (b) endpoint buoy object.

Participants were required to complete navigation tasks in a virtual environment. The primary objective was to guide the boat from a starting point to an end point (buoy) while navigating around obstacles, including wooden barrels, logs, and islands, in a virtual environment. Participants were instructed to minimize obstacle collisions and complete the task as quickly as possible. Participants operated a minimalist boat that moved only forward at three distinct speeds (500, 650, and 750 units/s), with yaw steering controlled via a joystick. Participants binocularly observed the virtual scene with a $120°$ field of view. They could freely rotate their heads while maintaining a stable environment and interface during navigation.

The virtual navigational environment covered a 500 x 500 unit grid, represented realistic navigation scenarios, incorporating natural terrain. Islands possess sandy shores, grassy zones, trees, and rocks, creating an organic coastal landscape (see Figure 3.1a). Two island-density setups were used: ten and twenty islands (see Figure 3.3). Islands were placed pseudo-randomly on a grid, such that their location was unpredictable from one run to the next, keeping a 20m minimum distance. In the ten-island condition (low environmental clutter), irregular landforms created narrow channels and elongated paths, while the twenty-island condition (high environmental clutter) comprised smaller, circular islands in a maze-like pattern, needing frequent directional choices (see Figure 3.3). Contact with the buoy prompted a scene switch, indicating task completion (see Figure 3.1b).

Figure 3.2: Types of floating obstacle objects

In each scenario, 80 floating obstacles from the 11 obstacle types were dispersed pseudo-randomly throughout the virtual environment. The 11 floating obstacle types, including naval mines, wooden boxes, planks, and logs (see Figure 3.2). These obstacles were visually distinct on the water surface, allowing them to drift gently.

3.1.2 Head Mounted Display Interface Information

(a)

(b)

Figure 3.3: Top-Down Schematic of the Virtual Maritime Environment. (a) Low environmental clutter condition with 10 islands. (b) High environmental clutter condition with 20 islands.

The HMD featured fundamental navigational details via a minimalist interface that maintained forward visibility. It displayed eight components: a minimap showing the vessel, endpoint buoy, and nearby terrain (but not floating objects); a speedometer (m/s); a distance-to-target gauge (m); a compass; a static weather icon; a battery level indicator; a voice-call icon; and a naval codename (e.g., "Alpha") (see Figure 3.4). In the low display clutter condition, there were four relevant objects on the display: the minimap, speedometer, distance-to-target gauge, and compass were task-relevant. All of those objects could legitimately be used by participants to navigate. In the high display clutter condition, shown in the bottom row of Figure 3.4, four additional items were included that were not relevant to the participants' task. The entire interface for low and high display clutter used less than 45% of the display area, where the minimap covered approximately 26%. Therefore, the environmental clutter impacted each of the interface elements, rather than any specific items. Moreover, the minimap was a zoomed-in version that translated and rotated with the boat to show a small section of the map around the user as they traveled.

3.1.3 Technical Specifications

Participants used an HTC VIVE Focus 3 standalone head-mounted display (HMD), which featured dual 2.88-inch LCD panels (2,448 x 2,448 pixels per eye, 90 Hz, 120° field of view). Steering was achieved with the right-hand controller joystick, acceleration with the trigger, and deceleration with the thumb grip. Virtual environments were entirely developed in Unity 3D (version 2022.3.35f1 LTS) within the HMD. A custom C# script recorded each participant's task completion time and proximity data, saving the data to .csv files stored locally on the headset.

3.2 Independent Variables

Environmental clutter: Environmental clutter was defined by the number of islands in a virtual environment surrounded by a water body. We assumed that the floating objects, being small and not salient, would not act as clutter to the detriment of processing the displayed information, and hence their number was kept constant across both levels of environmental clutter. The low- and high-clutter conditions included 10 and 20 islands, respectively (see Figure 3.3).

Display clutter: Display clutter was referred to the number of display interface elements. As described above, the low-clutter condition included four functional, task relevant navigational indicators: speed, distance to target, mini map, and compass heading [32]. The high-clutter condition added four additional, non-functional, task-irrelevant items [52].

Display Opacity (transparent, opaque): Display opacity was manipulated via the alpha channel of the display shader in the Unity program. Display opacity has two levels: transparent, when

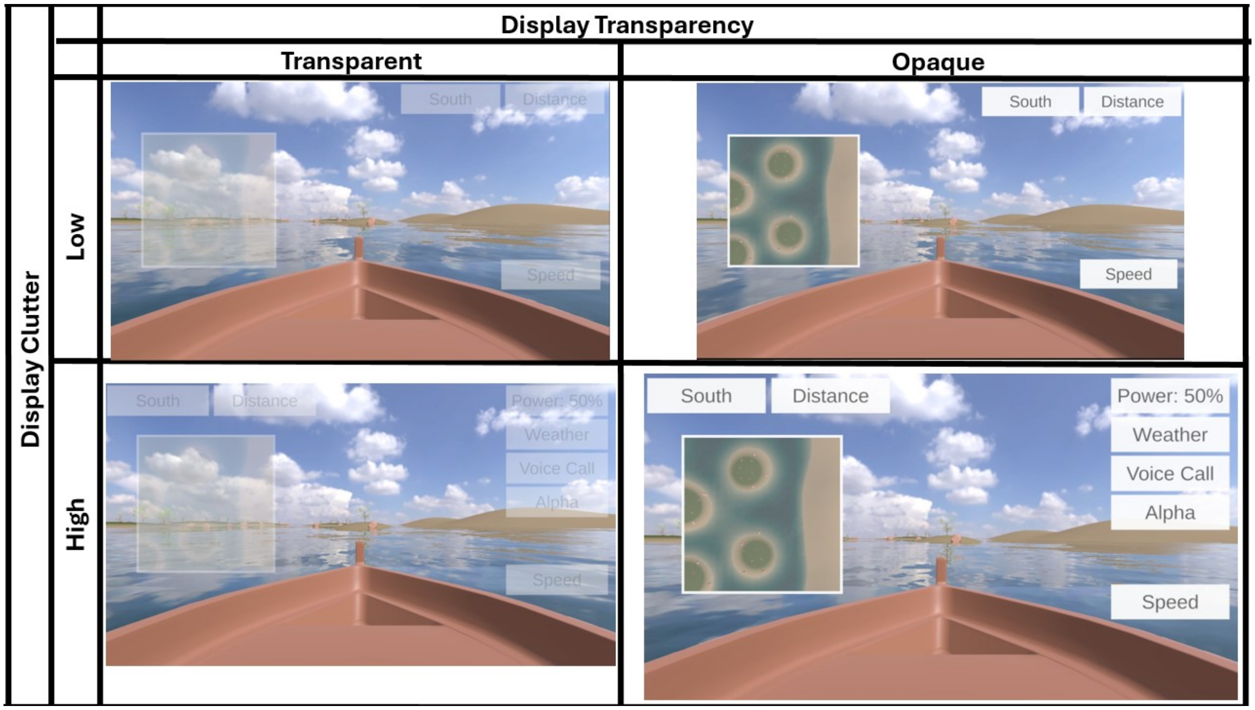


Figure 3.4: Display Clutter and Transparency conditions

the virtual interface element has an opacity of 0.5, and opaque, when the virtual interface element has an opacity of 1.0.

3.3 Dependent Variables

Navigational performance was assessed using two primary dependent variables: completion time and proximity to hazards. Completion time (in seconds) was measured from trial onset (start-cue scene) to the endpoint buoy contact. We continuously assessed the proximity of the boat to objects or islands to detect both collisions and incidents classified as "unsafe close penetrations" within 8 meters beyond the boundaries of these islands and obstacles (proximity to hazards). These values were recorded and saved by the Unity program for each trial that the participants performed.

3.4 Experimental Design and Procedure

This study employed a fully within-subjects factorial design, with participants completing navigation tasks under all combinations of three independent variables (environmental clutter, display clutter, and transparency). Each of the eight conditions was presented twice, for a total of 16 trials per participant. The trial order was block-randomized to avoid consecutive repetition, and start/end locations varied to prevent route memorization. Before data collection, participants completed an informed consent form, a demographic questionnaire, and a baseline NASA-TLX assessment. Headset IPD was adjusted nearly to the measured interpupillary distance (IPD) with a pupilometer, ensuring maximum comfort. Participants were informed they could pause or request assistance at any time. Participants navigated while seated in a controlled lab setting with stable lighting and minimal distractions.

The training phase introduced HMD, controls, and collision/reset mechanics. In an environment with one hazard element (e.g., a house) and a target buoy in sand, participants practiced steering, speed modulation, and collision response. Advancement to reach the experimental trials required three successful completions and one intentional collision. After the training phase, participants performed the experimental trials. Participants were instructed to navigate to the buoy as rapidly and directly as possible, while still avoiding collision with any of the islands or floating hazards. The location of the buoy was randomly placed in such a way that the distance from the start position to the buoy was 450 meters in each trial. The buoy could not be seen from the initial position. It could only be seen when the boat was 100 meters away from the buoy in the minimap, as well as in the forward FOV when no obstacles were present.

After each trial, participants verbally completed the NASA-TLX survey. One-minute rests followed each trial, with a 10-minute break at the midpoint. After all experimental trials were concluded, participants engaged in a brief debriefing session during which they reported any discomfort, nausea, or other adverse effects. Finally, participants received gratitude and appropriate compensation. The entire experiment lasted approximately 1 hour and 15 minutes.

3.5 Participants

Priori power analysis in G*Power 3.1 [53] indicated that 28 participants would be required to achieve 80% power to detect a medium effect size (f = 0.25) in a repeated-measures ANOVA. Therefore, we recruited a total of 30 volunteers (17 male, 12 female, and 1 non-binary; mean age:

24.3 years; age range: 18-38 years) from the Colorado State University community. All participants had normal or corrected-to-normal vision, no history of vestibular or neurological disorders, and minimal prior motion-sickness susceptibility. Twenty participants received a $20 Amazon gift card; the remainder participated without compensation. The Colorado State University Institutional Review Board approved all procedures, and written informed consent was acquired following the Declaration of Helsinki.

3.6 Results

3.6.1 Data Pre-Processing & Analysis

Repeated measures ANOVAs analyses were conducted to evaluate the effects of our experimental variables. All analysis was performed in R using ANOVA as well as Bonferroni tests. ANOVA analysis was done using the ez package, while the Bonferroni tests were done using the Desc-Tools package. For effect size, we report the partial generalized eta squared (η_p^2), with interpretations as follows: small ($\eta_p^2 = 0.01$), medium ($\eta_p^2 = 0.06$) and large ($\eta_p^2 = 0.14$). Based on the Shapiro-Wilk Test and histogram plots, both the performance metrics and the scores from the NASA TLX violated normality assumptions. Both were log-transformed to mend this violation. Despite these transformations improving the normalized distribution, they did not eliminate the violation entirely; however, ANOVA is robust to these violations when the sample size is moderate to large [54, 55], the analysis reported here is a moderate sample size (N = 30). Statistical significance was measured using the standard alpha = 0.05 measure throughout the analysis.

3.6.2 Efficiency (Completion Time)

Completion time was measured in seconds, representing the time it took the participant to travel from the starting location to the target buoy at the other side of the navigation space. This data was processed by calculating the mean for each participant across the two repetitions; subsequently, the means were log-transformed.

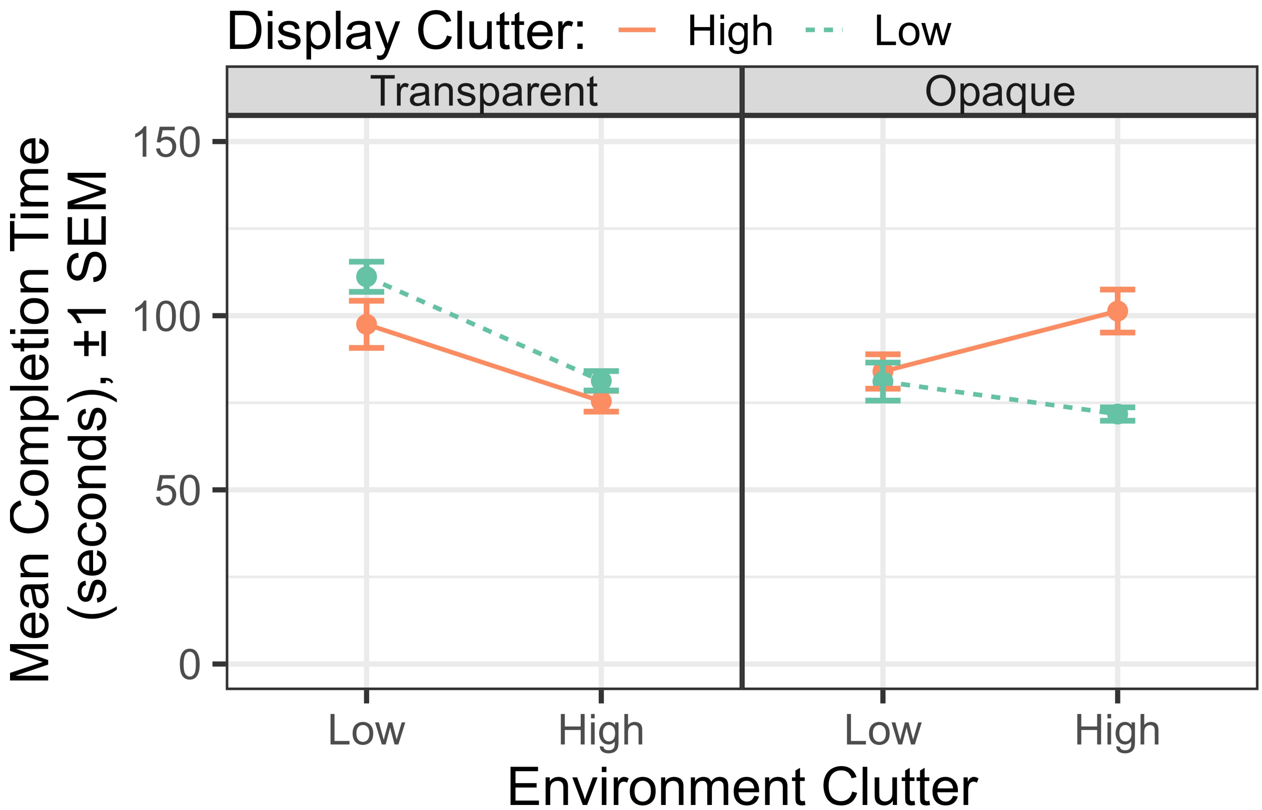


Figure 3.5: Mean of Completion Time. These values are then split between opacity: transparent and opaque. Additionally, Display clutter can be visualized with high display clutter represented by green and low display clutter represented by orange. Lastly, the x-axis shows the low and high environmental clutter. Error bars represent one standard error of the mean.

The analysis of mean completion time depicted in Figure 3.5 showed that the time was significantly shorter with high environmental clutter $(F(1,29) = 17.20, p < .001, \eta_p^2 = .04)$. Completion time was also significantly shorter when the display was opaque $(F(1,29) = 14.09, p < .001, \eta_p^2 = .04)$. The significant 2-way interaction between environmental clutter and transparency $(F(1,29) = 42.46, p < .001, \eta_p^2 = .12)$ indicated that this speeding with opaque displays was only observed under conditions of low environmental clutter (the right half in Figure 3.5).

While display clutter did not affect completion time $(F(1,29) = 0.64, p = 0.43)$, the significant interaction between display clutter and transparency showed that high display clutter slowed completion time when the display was opaque (right panel), but not when the display was transparent (left panel; $F(1,29) = 39.37, p < .001, \eta_p^2 = .10)$. The significant 2-way interaction between environmental clutter and display clutter $(F(1,29) = 14.11, p < .001, \eta_p^2 = .04)$ shows that low display clutter was only observed to be faster under conditions of high environmental clutter. Subsequently, the three-way interaction between the variables showed a non-significant trend $(F(1, 29) = 3.12, p = 0.08, \eta_p^2 = .01)$ between the two-clutter condition interaction above, was present when the display was opaque.

3.6.3 Safety (Proximity Entry)

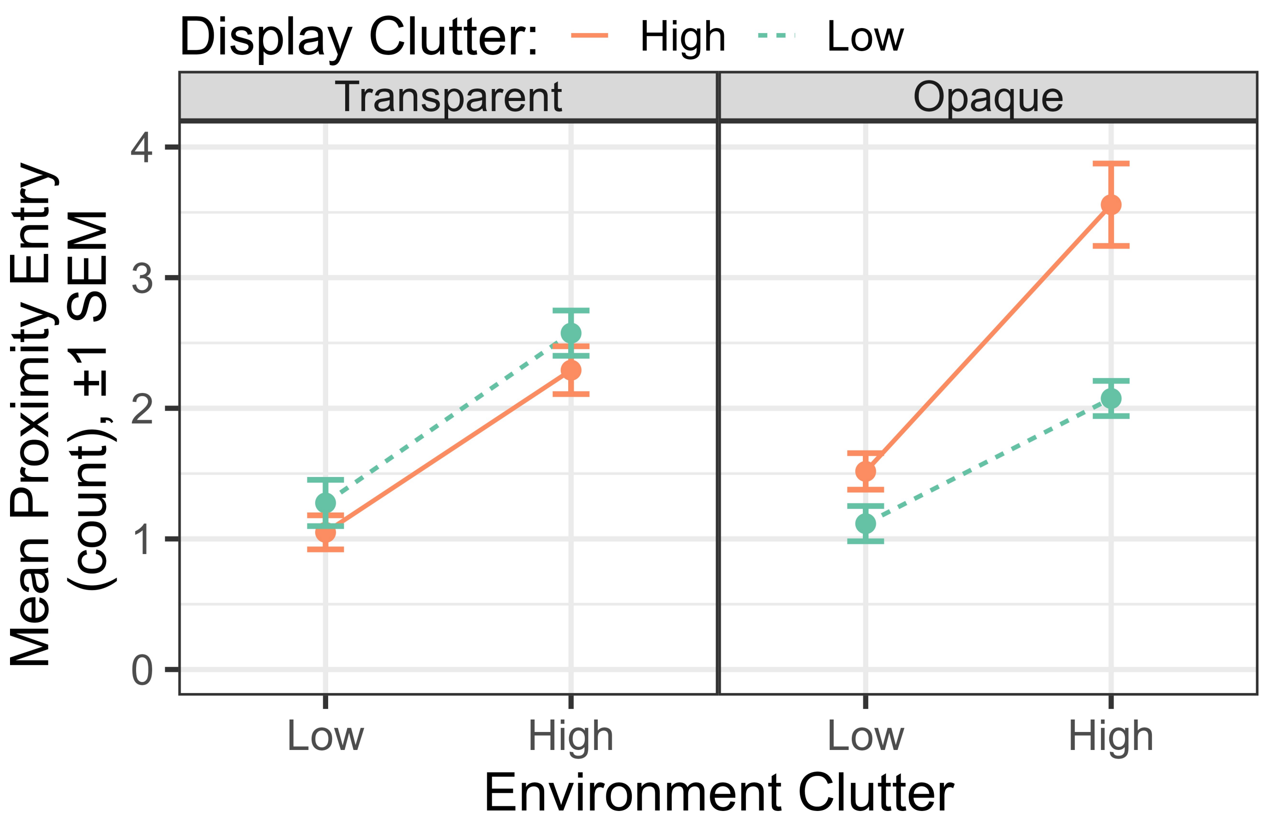


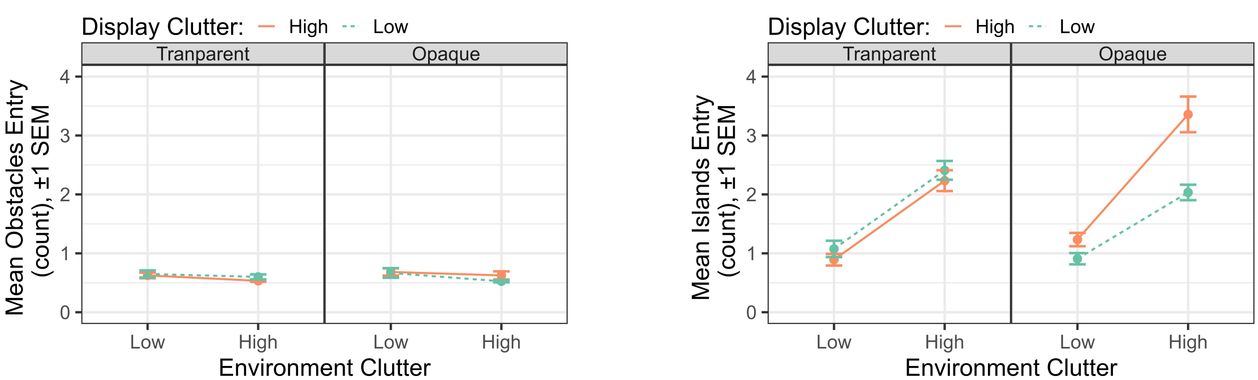
Figure 3.6: Mean of Proximity Entry. These values are then plotted according to the opacity level, environment clutter, and display clutter. Error bars represent one standard error of the mean.

Proximity entry, violating safety constraints, was calculated whenever the boat crossed an 8-meter limit surrounding either islands or floating hazards. These were counted for each trial. There were very few actual collisions with islands, so safety was defined only by the penetration of the safety zone around the islands.

Figure 3.6 presents the findings for unsafe proximity entry. ANOVA on the log-transformed data revealed that, as with completion time, high environmental clutter led to more proximity entries $(F(1,29) = 208.70, p < .001, \eta_p^2 = .40)$. Proximity entry also increased when the display was more opaque $(F(1,29) = 7.77, p < .01, \eta_p^2 = .02)$. The interaction between environmental clutter and transparency was not significant.

The significant effect of display clutter showed that safety violations were higher for high clutter $(F(1,29) = 4.95, p < .05, \eta_p^2 = .02)$. However the statistically significant interaction between display clutter and transparency indicated that higher display clutter increased safety violations only when the display was opaque, and not when it was transparent $(F(1,29) = 33.66, p < .001, \eta_p^2 = 0.08)$. The 3-way interaction between the variables was not significant $(F(1,29) = 0.45, p = 0.51)$.

To follow up on this analysis, we examined separately whether the penetrations were related to islands or the floating hazards. Figure 3.7 depicts the same data as Figure 3.6, but now broken down separately by penetrations of floating objects (left) or islands (right). It is apparent that obstacle penetrations were minimal and not affected by the independent variables. Thus, the composite effects shown in Figure 3.6, are exclusively associated with penetrations of the unsafe space surrounding the islands.



(a) (b)

Figure 3.7: Individual graphs for Mean Obstacles and Mean Island Proximity Entry. These values illustrate the difference in hazards from the Mean Proximity Entry and were plotted according to opacity level, environmental clutter, and display clutter. Error bars represent one standard error of the mean

3.6.4 Mental Workload TLX

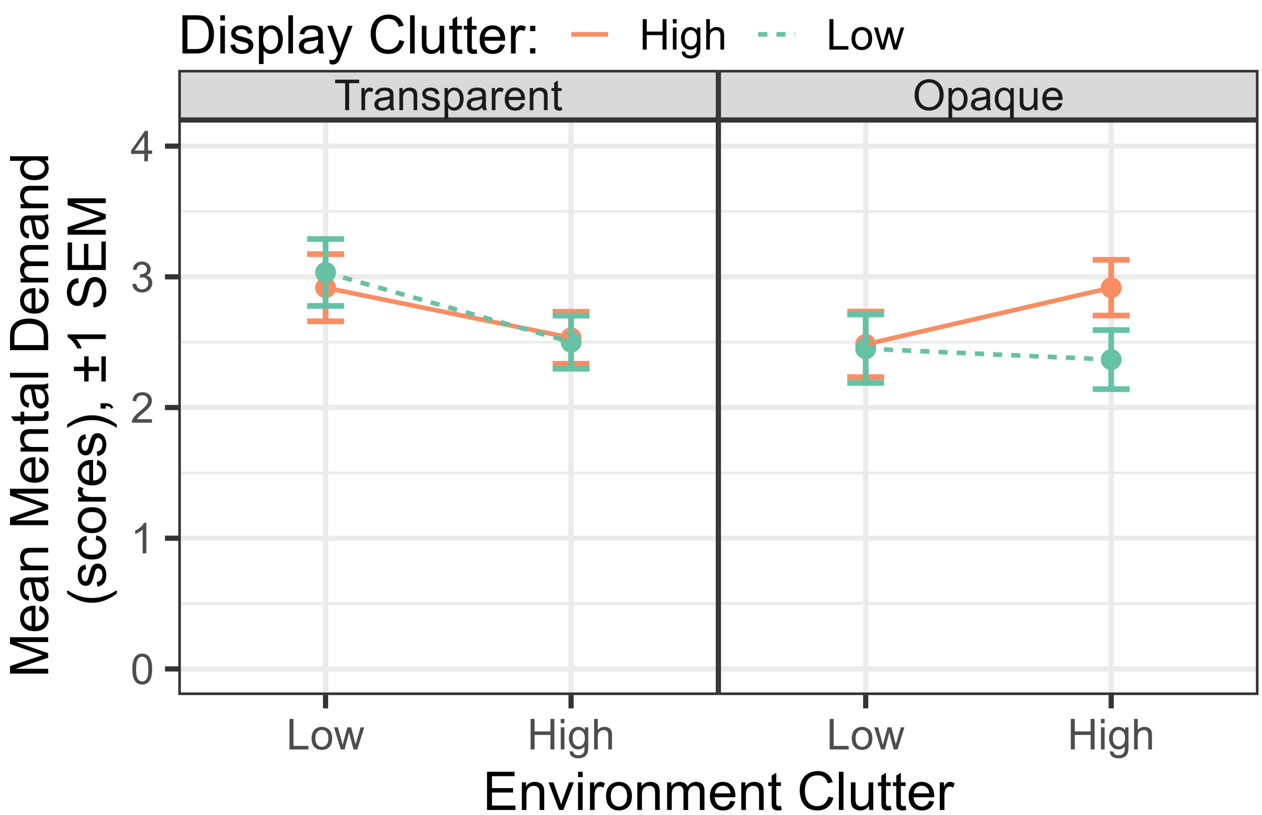


Figure 3.8: Mean of Mental Demand. These values are then plotted according to the opacity level, environment clutter, and display clutter. Error bars represent one standard error of the mean.

While participants rated all six subscales of the TLX rating scale, in the current analysis, we focused exclusively on the mental demand scale. The other subscales were excluded because mental demand captured participants' cognitive effort, decision-making, and attention during the experimental task. Figure 3.8 presents the NASA TLX mental demand rating as a function of clutter and transparency. An ANOVA on these data revealed that there was no effect of environmental clutter $(F(1, 203) = 3.22, p = 0.074)$ but significantly higher workload when the display was transparent $(F(1, 203) = 18.59, p < .001)$. There was also a statistically significant interaction between environmental clutter and opacity, such that low environmental clutter increased workload when the display was transparent, but not when it was opaque $(F(1, 203) = 5.83, p < .05)$. Furthermore, during our debrief, 6 out of 30 participants reported nausea, blurry images, and dizziness as discomfort after finishing the experiment.

3.7 Discussion

In the current experiment, we evaluated the effects of two properties of the HMD – display transparency (versus opacity) and display clutter –along with an important property of the environment in which it is deployed – its clutter – in order to assess how these three features would influence the efficiency and safety of performance in a nautical navigation task. Below, we describe how the results initially impact efficiency and then safety, followed by a discussion of their effects on mental workload. The effects we describe are assumed to be mediated by three information processing variables: a cognitive variable related to the strategic choice of speed, a perceptual variable related to the degraded legibility of relevant display information, and an attentional/perceptual variable related to the distracting effects of overlay clutter [21].

3.7.1 Efficiency

We measured efficiency in terms of the environmental transit time. A preliminary analysis revealed that all of the influences of our three variables on transit time were imposed on the mean speed of travel, rather than the distance travelled. A slower speed, we reasoned, was a result of greater caution or less confidence in navigating the water safely, and hence a conscious choice to use lower throttle settings. For each measure, we evaluated three hypotheses:

H1a proposed that increasing environmental clutter, here the number of islands would lead to slower travel. In fact, we found the reverse: more islands yielded faster transit, particularly and consistently when the display was transparent (display interface elements were hard to interpret), and hence environmental objects were highly visible in the field of view. We reasoned that this strategic choice to travel faster was guided by better visibility of environmental objects: if you can see them better, you travel faster. And if you can see smaller objects (Islands) more clearly, it further influences the decision to travel faster.

H1b proposed that transparency, and hence greater visibility of objects would slow travel because of greater caution exercised by the participants, and this was in fact found; particularly when there was low environmental clutter; that is, fewer, but larger, islands to be seen, a conclusion supported by the large interaction of the two variables, visualized in Figure 3.5.

H1c proposed slower travel with the more display clutter, an effect observed only with the opaque display (Figure 3.5) where the obscuration would "hide" more islands.

3.7.2 Safety

In terms of the penetrating safety violations with islands and hazards, our results revealed that nearly all of these, as well as the effects thereon, were witnessed by penetration of, or near collisions with islands, rather than with floating hazards.

H2a proposed more penetrations in a more cluttered, island-rich environment, and this was indeed strongly confirmed in Figure 3.6. Indeed, this effect of environmental clutter on safety penetrations could be predicted on purely statistical grounds: with twice as many islands (20 versus 10), participants choosing to navigate just within the bounds of safety nevertheless penetrated approximately twice as often $(M = 2.7, SE = 0.17 vs M = 1.3, SE = 0.17)$. Figure 3.6 shows that this environmental clutter effect is relatively independent of the level of the other two variables, a pattern reflected by the absence of interactions.

H2b proposed that the opaque display, more obscuring of hazards, would increase the number of penetrations with those hazards, and, indeed, it did so. However, the interaction and the visual trend seen in Figure 3.6 indicated that this increased penetration rate was only observed under conditions of high display clutter, when, of course, there are more of those islands to be somewhat obscured by the opacity of the display.

Finally, H2c proposed that the increase in display clutter would partially obscure more environmental objects and hence lead to more "near collisions" with them, and this was indeed confirmed, although, as noted, only when those objects (islands) were more obscured by the more opaque display. Thus, display clutter and opacity both amplified each other's degrading effect on safety.

The pattern of effects of the three variables on mental demand (Figure 3.8) appeared to closely mimic those on completion time (Figure 3.5), as did the pattern of statistical effects on the two variables. This would suggest that participants are highly sensitive to the factors that caused a delay, and use these as a proxy for their post-trial rating of mental demand.

Given the overall pattern of results, an HMD systems designer may wish to assess which combination of display features provides the most effective HMD design in nautical navigation. Here, the pattern of data provides no clear guidance, although they do suggest that when navigating in a highly cluttered environment, the poorest design for both efficiency and safety is an opaque display with high display clutter. However, such guidance is quite tentative at this point and requires considerably more research in which, in particular, more than a single level of transparency is examined. The current data also support the viability of theory-based metrics of clutter in predicting performance in this operational task. Collectively, the data reveal only partial success in this endeavor. Employing the well-validated object-count metric of clutter [20, 21], our manipulations doubled the amount of both display and environmental clutter. Doubling environmental clutter (twice as many islands) produced a clear performance decrement of slightly more than doubling the number of unsafe proximity violations (Figure 3.7). However, it had no effect at all on completion time, suggesting the existence of a speed-accuracy tradeoff. It is quite possible that any negative effect of doubling the number of islands was offset by the benefit of increasing the ability to find a straighter path through them.

Doubling display clutter, and hence doubling the amount of either full (opaque) or partial (transparent) occlusion of the environmental hazards, appeared to have the predicted effect only when the display was in the fully occluded mode (right panels of Figures 3.6 and 3.7). Under this condition, the doubling of clutter nearly doubled the number of safety-violating penetrations and significantly increased completion time (no speed-accuracy tradeoff). However, the transparent display, whose goal was to decrease the clutter costs, expectedly reduced the clutter effects; but by effectively eliminating these costs altogether, it thereby rendered the clutter metric useless.

Chapter 4

Experiment 2

One limitation of Experiment 1 was a fixed optical distance between the HMD imagery and the scene beyond. When viewing a distant scene, the collimation of HMD information at long distances approaching optical infinity would be expected to reduce attention-switching time between the two domains, potentially benefiting performance. However, removing this distance differential cue could impair the ability to focus on one domain while ignoring the other. Following Experiment 1, we conducted a second experiment aimed at extending this work to understand the effects of clutter on this element of HMDs: optical distance. Optical distance of an HMD display is the distance between the VR-rendered display interface and the operator. This is typically achieved by manipulating the binocular disparity between the two images presented through the HMD lens. Moving the distance between the two images to 2 m or 10 m affects the angle of the left and right eyes relative to the display, creating depth perception. Increasing this optical distance also decreases the visual angle of the display proportionately, just as would be the case of the real distance to a display. Along with this additional element, head-tracking data were also collected during each condition to better understand participants' scanning behavior. This partial replication of the prior experiment kept a consistent display transparency, with display opacity around 0.5 –similar to the transparent virtual interface of Experiment 1.

In aviation, designers prioritize text legibility, as missing critical information can result in unstable flight paths [56] and mitigate risks for approach and landing phases of flight [6]. This contrasts with our current experiment and our usage of optical distance of an HMD display. In Experiment 2, we manipulated the distance of our HMD interface to 2 meters and 10 meters, without a constant visual angle, which would keep the HMD interface information at a consistent size. The HMD interface changed size and was not consistent between the two distances; the HMD interface size was not increased proportionately. This means that the HMD interface at 2 m has a larger display size; the HMD interface at 10 m has a proportionately smaller (80%) display size.

Despite its smaller size, the 10 m interface was still visually legible, and the critical information on the display was usable in helping participants reach the endpoint buoy on the mini-map. Optical distance was manipulated in works such as Arefin et al. [28], who discussed transient focal blur, a biological process that takes around 425 milliseconds for the eyes to return to sharp focus, which could potentially lead to missing critical information in the scene surrounding them when switching between near domain information and far domain information. In Warden et al. [21], they discuss the biological mechanism of peripersonal space, which could lead to missing critical information in the far domain due to priority being given to the near domain. In Flittner and Gabbard's work [50], they found that visual search of a display at 4 and 6 meters had longer search times than at 2 meters. In Masnadi et al. [49], they found that increased environmental clutter led to more precise distance judgments when performing a blind walking task to targets placed at 3, 4.5, and 6 meters away. In addition, they also found trends of underestimation for the targets, and this error grew as targets were placed farther away. Imamov et al. [51] found that information presented at 3 meters reduced task completion time compared to the 1 and 2 meter distances because it was closer to the depth of the primary task, which was 4 meters. The manipulation of optical distance in HMDs supports the idea that information presented closer together in depth improves the performance of hazard avoidance. By presenting information at closer depths to the hazard, which are positioned, in the current paradigm, at a range of distances well beyond 2 meters, it should require less time for those hazards to be noticed and improve the avoidance of hazards (islands and obstacles). Optical distance in HMDs also supports the idea that information presented farther away reduces some level of legibility, especially if the display is not compensated by increasing the visual angle. The farther optical distance with the smaller display might hurt navigational performance by reducing the ability to discriminate the finer aspects in the minimap component. The aim of Experiment 2 is to analyze the effects of clutter, both display clutter and environmental clutter, alongside optical distance in the same nautical navigation task. In the following chapter, details are provided on the methods, variables, and experimental setup used to accomplish these goals.

4.1 Research Hypotheses

We hypothesize that:

H1: Navigational performance, in terms of completion time and distance traveled, will be:

- **H1a:** decreased (longer transit time and longer distance traveled) by increasing optical distance, because the smaller display will reduce legibility and hurt performance based on fine discriminations within the (now smaller) visual area.
- **H1b:** decreased (longer transit time and longer distance traveled) by increasing environmental clutter, because of the increase in the number of environmental hazards causing longer alternative routes.
- **H1c:** decreased (longer transit time and longer distance traveled) by increasing interface clutter, because of the increase in occlusion of the surrounding environment due to the HMD interface.

H2: Navigational Safety, in terms of hazard collisions and proximity to hazards, will be:

- **H2a:** increased (decreased collisions with and proximity to hazards) by increasing optical distance, because the distance between the HMD interface and the environment is closer together, improves how hazards are noticed and avoided.
- **H2b:** decreased (increased collisions with and proximity to hazards) by increasing environmental clutter, because the increase in environmental hazards creates more safety boundaries to be aware of.
- **H2c:** decreased (increased collisions with and proximity to hazards) by increasing interface clutter, because of the increase in partial occlusion of the surrounding environment.

H3: Horizontal Head Tracking data during navigation will show:

- **H3a:** decreased head rotation from increasing optical distance, because the increased distance will make the HMD interface smaller, requiring less visual scanning of the map for island hazards.

H3b: increased head rotation from increasing environmental clutter, because the increase in the number of environmental hazards creates more island safety boundaries to be aware of, requiring more visual scanning.

H3c: increased head rotation from increasing interface clutter, because of the increase in partial occlusion of the surrounding environment requiring more visual scanning.

4.2 Apparatus and Setup

4.2.1 Virtual Environment and Task

The virtual environment and task were identical to those in Experiment 1, except that floating obstacles were an additional factor that differed between the low and high environmental clutter conditions. The obstacles had 50 and 100 hazards in the low and high clutter conditions, respectively.

4.2.2 Head Mounted Display Interface Information

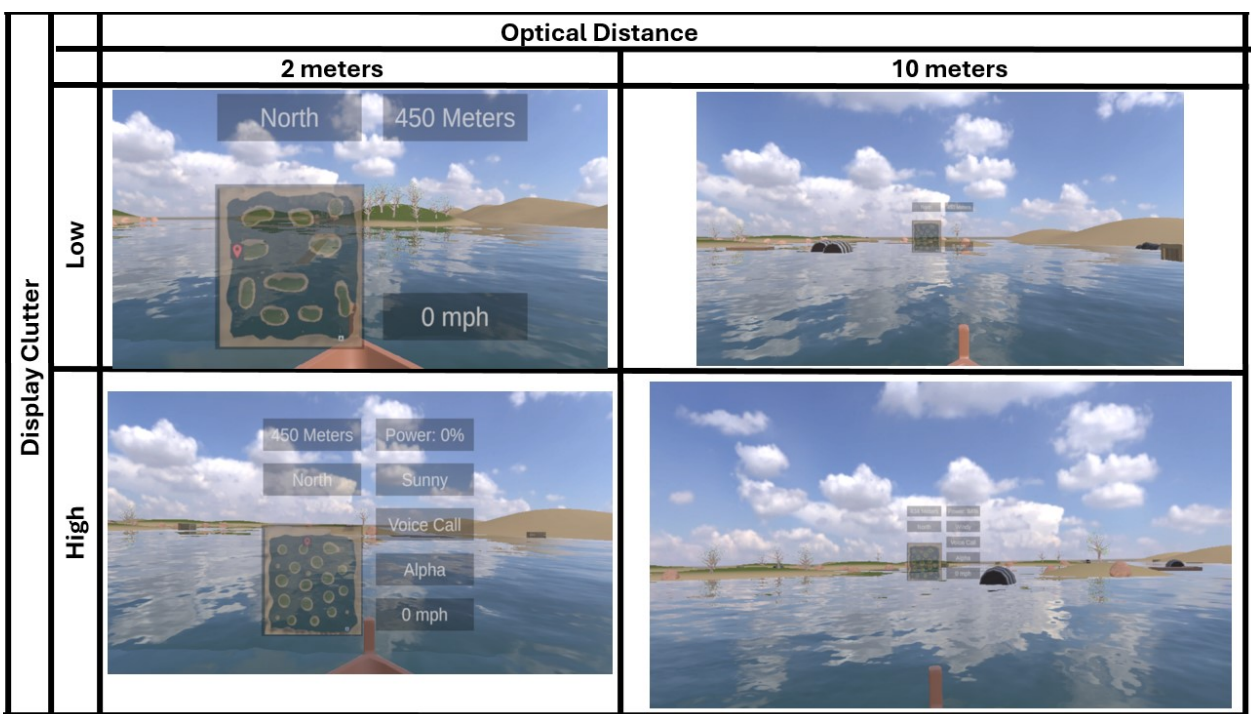


Figure 4.1: Display Clutter and Optical Distance Conditions

The interface information are similar to Experiment 1's, but contains a few differences, specifically:

HMD Interface The HMD interface now rotates and moves along with the participant's head movement, so that all display information is constantly in the center of the participant's field of view. In Experiment 1, the interface maintained forward visibility, meaning that it was static, presented in world-referenced coordinates, and always aligned with the nose of the boat. Additionally, the interface color was changed to black, compared to the white fog design in Experiment 1. The alpha channel of the display shader in Unity is 0.5 for both Experiment 1 and Experiment 2. Meaning that both displays are the same level of transparency; just the underlying color of the interface was changed to black. This follows a similar setup of optical see-through HMDs that use augmented reality, as when the virtual overlaid information has an underlying black coloring, it makes the information transparent, meaning that the real world is partially occluded by the interface. We attempted to replicate this setup to better match existing headsets like the Microsoft HoloLens 2 and their rendering of virtual information.

Mini-map Component The interface components remained the same, with 8 for the high display condition and 4 for the low display condition; however, the position of information boxes was changed and is visible in Figure 3.4 with Figure 4.1. The position of the boxes was moved closer together to the center of the display to keep everything in frame and readable to the participant. The minimap component was changed to show the entire virtual environment on the map rather than showing a slice of the virtual environment by rotating with the boat. The mini-map now depicted the floating obstacles, the terrain, the endpoint buoy, and the vessel as seen in Figure 4.2. The map was consistently presented in a north-up orientation. The visibility of the floating obstacles is a change from Experiment 1, as now the floating obstacles are represented on the mini-map.

HMD Display Transparency The HMD interface element of transparency is now at a consistent value of 0.5 across all conditions, and this independent variable has been replaced with optical distance. The consistent display transparency had an opacity of around 0.5 via the alpha channel of the display shader in the Unity program. This value was chosen because it showed the best performance in Experiment 1, increasing completion time and reducing proximity hazards in the environment.

Optical Distance Two levels of optical distance were examined, 2 m and 10 m. These distances were chosen as they represent examples of the extremes in displaying HMD information. 10 meters is when information begins to approach optical infinity, which should help keep near and far domain information in focus [7, 46]. Warden et al. [22] discuss how motion and stereo depth cues begin to diminish in effectiveness after 10 meters, which will make it harder to focus on one domain while ignoring the other. During the pilot data collection, the information was harder to read along the edges of the interface at distances closer than 2 meters, since the interface moved along with head orientation. The 2-meter interface did not have this issue with the edges and was chosen for this reason.

4.3 Independent Variables

Environmental clutter: Environmental clutter was defined by the number of islands and floating objects in a virtual environment surrounded by a water body. The low- and high-clutter conditions included 10 and 20 islands, respectively, in addition to the 50 and 100 floating obstacles.

Display clutter: Display clutter remained the same and referred to the number of display interface elements. As described above, the low-clutter condition included four functional, task-relevant navigational indicators: speed, distance to the target, mini-map, and compass heading [32]. The high-clutter condition added four additional, non-functional, task-irrelevant items.

(a)

(b)

Figure 4.2: Top-Down Schematic of the Virtual Maritime Environment. (a) Low environmental clutter condition with 10 islands. (b) High environmental clutter condition with 20 islands.

Optical Distance (2 m, 10 m): Optical distance was manipulated by increasing the distance between the participant and the display interface. Optical distance has two levels: 2 m, when the virtual interface is 2 meters away from the participant, and 10 m, when the virtual interface is 10 meters away from the participant. Hence, as is evident from Figure 4.1, the farther optical distance simultaneously occupies less space and potential scene clutter; but at the same time, is smaller and can reduce the legibility of the displayed information by reducing the ability to discriminate the finer aspects in the display like those in the minimap.

4.4 Dependent Variables

Navigational performance was assessed in two ways: navigational efficiency and navigational safety. Navigational efficiency was determined by completion time (in seconds), which was measured from trial start to contact with the endpoint buoy; and by distance traveled (in meters), which was measured as the travel route the participant took to the endpoint buoy. Navigational safety was determined by collisions with and proximity to hazards, the latter classified by entry into an 8-meter boundary surrounding islands and obstacles. Head tracking was also assessed and measured the absolute horizontal gaze excursion of the participants from the nose of the boat in degrees. These values were recorded and saved by the Unity program for each trial that the participants performed.

4.5 Experimental Design and Procedure

Participants completed navigation tasks under all combinations of three independent variables (environmental clutter, display clutter, and optical distance) under a fully within-subjects factorial design. Each participant completed 16 trials, as each of the eight conditions was presented twice. The trial order was block-randomized to avoid consecutive repetition, and start/end locations varied to prevent route memorization. To further elaborate on this, the number of islands depended on the environmental clutter as the position of the islands stayed across trials depending on the setup (the 10 island or the 20 island). We then varied the start and end locations to prevent memorization but always kept the end target within 450 meters away from the starting point. At the beginning of the experiment, participants completed an informed consent form and a demographic questionnaire. The headset IPD was adjusted to nearly the measured interpupillary distance (IPD) with a pupilometer, ensuring maximum comfort. Participants were informed they could pause or request assistance at any time. Participants navigated while seated in a controlled lab setting with stable lighting and minimal distractions.

The training phase and the end of each trial were identical to those in Experiment 1. The entire experiment lasted approximately 1 h and 15 min.

4.6 Technical Specifications

The technical specifications are identical to those of Experiment 1.

4.7 Participants

Priori power analysis in G*Power 3.1 [53] indicated that 24 participants would be required to achieve 80% power to detect a medium effect size (f = 0.25) in a repeated-measures ANOVA.

Therefore, we recruited a total of 24 volunteers (17 male, 5 female, and 2 non-binary; mean age: 24.6 years; age range: 20-32 years) from the Colorado State University community. All participants had normal or corrected-to-normal vision, no history of vestibular or neurological disorders, and minimal prior susceptibility to motion sickness. Twenty-four participants received a $20 Amazon gift card. The Colorado State University Institutional Review Board approved all procedures, and written informed consent was obtained in accordance with the Declaration of Helsinki.

4.8 Results

4.8.1 Data Pre-Processing & Analysis

Repeated measures ANOVAs were conducted to evaluate the effects of our experimental variables. All analyses were performed in R using ANOVA and Bonferroni tests. ANOVA analysis was done using the ez package, while the Bonferroni tests were done using the Desc-Tools package. For effect size, we report the partial generalized eta squared (η_p^2), with interpretations as follows: small ($\eta_p^2 = 0.01$), medium ($\eta_p^2 = 0.06$) and large ($\eta_p^2 = 0.14$). Based on the Shapiro-Wilk Test and histogram plots, both the performance metrics (efficiency and safety) violated the assumption of normality. Upon reviewing this violation, we examined the data for outliers and identified four values from one participant that were not similar to the rest of the data. These values were in completion time, distance traveled, total far proximity, and far island proximity. After removing these values by setting them to the median across all participants and repetitions, the performance metrics were log-transformed to address this violation. After the transformation, no additional outliers were found. Statistical significance was assessed using the standard alpha level of 0.05 throughout the analysis.

4.8.2 Efficiency (Completion Time and Distance Traveled)

Completion time was measured in seconds and is the time it took the participant to go from the starting location to the target. The analysis showed a statistically significant main effect of the environment, ($F(1, 23) = 29.85, p < .05, \eta_p^2 = .08$). Figure 4.3 shows that increasing en-

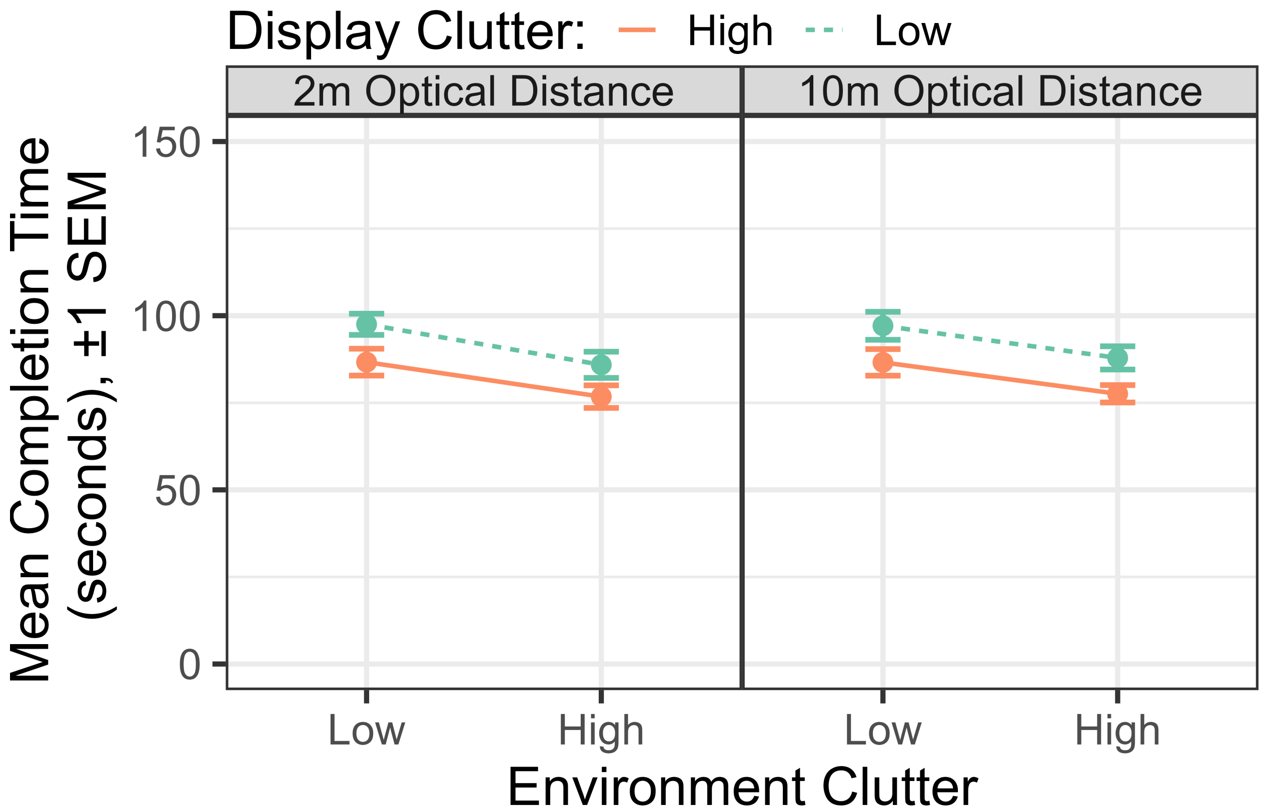


Figure 4.3: Mean of Completion Time. These values are then split between optical distances: 2 m and 10 m. Additionally, Display clutter can be visualized with high display clutter represented by green and low display clutter represented by orange. Lastly, the x-axis shows the low and high environmental clutter. Error bars represent one standard error of the mean.

vironmental clutter prompted faster completion times. There was a statistically significant main effect of display $(F(1,23) = 38.42, p < .05, \eta_p^2 = .1)$. In Figure 4.3, higher display clutter, on average, led to faster completion times. There was no significant main effect of optical distance, $(F(1,23) = 0.25, p = 0.62, \eta_p^2 = .0007)$.

Distance traveled was measured in meters and is the distance the participant traveled from the starting location to the target. The analysis showed a statistically significant main effect of the environment, $(F(1,23) = 29.21, p < .05, \eta_p^2 = .13)$. Higher environment clutter prompted shorter distances, as seen in Figure 4.4. There was a statistically significant main effect of display $(F(1,23) = 25.35, p < .05, \eta_p^2 = .15)$. Figure 4.4 shows higher display clutter prompted shorter distances. In addition, there was a statistically significant main effect of optical distance $(F(1,23) = 9.98, p < .05, \eta_p^2 = .03)$. Smaller (2 M) optical distance prompted shorter distance

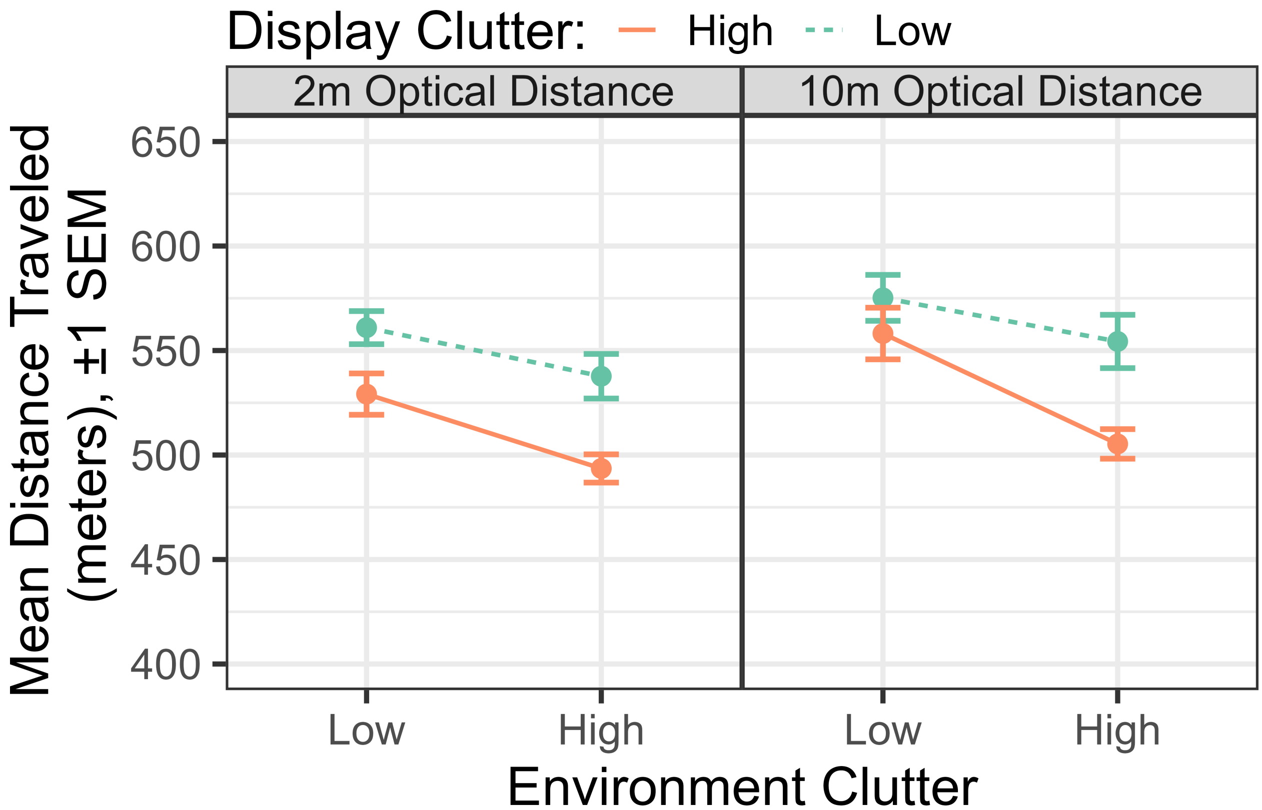


Figure 4.4: Mean of Distance Traveled. These values are then split between optical distances: 2 m and 10 m. Additionally, Display clutter can be visualized with high display clutter represented by green and low display clutter represented by orange. Lastly, the x-axis shows the low and high environmental clutter. Error bars represent one standard error of the mean.

traveled, as can be observed in Figure 4.4. Lastly, there was a statistically significant interaction between environment and display, $(F(1, 23) = 4.37, p < .05, \eta_p^2 = .01)$. This interaction can be seen in Figure 4.4, where the benefits of high display clutter are amplified when environmental clutter is high.

4.8.3 Safety (Proximity Entry)

Proximity entry was defined as when the participants entered the 8 meter radius that surrounded each obstacle and island. These counts were then processed by taking the mean of the two repetitions for each participant. The analysis of mean proximity entry showed a statistically significant main effect of environmental clutter, $(F(1, 23) = 133.39, p < .05, \eta_p^2 = .46)$. Higher environment clutter led to closer proximity to hazards. There was a statistically significant main effect of display $(F(1,23) = 52.47, p < .05, \eta_p^2 = .20)$. High display clutter, on average, prompted greater proximity to hazards. Finally, there was no significant main effect in optical distance, $(F(1,23) = 0.5, p = 0.5, \eta_p^2 = .001)$.

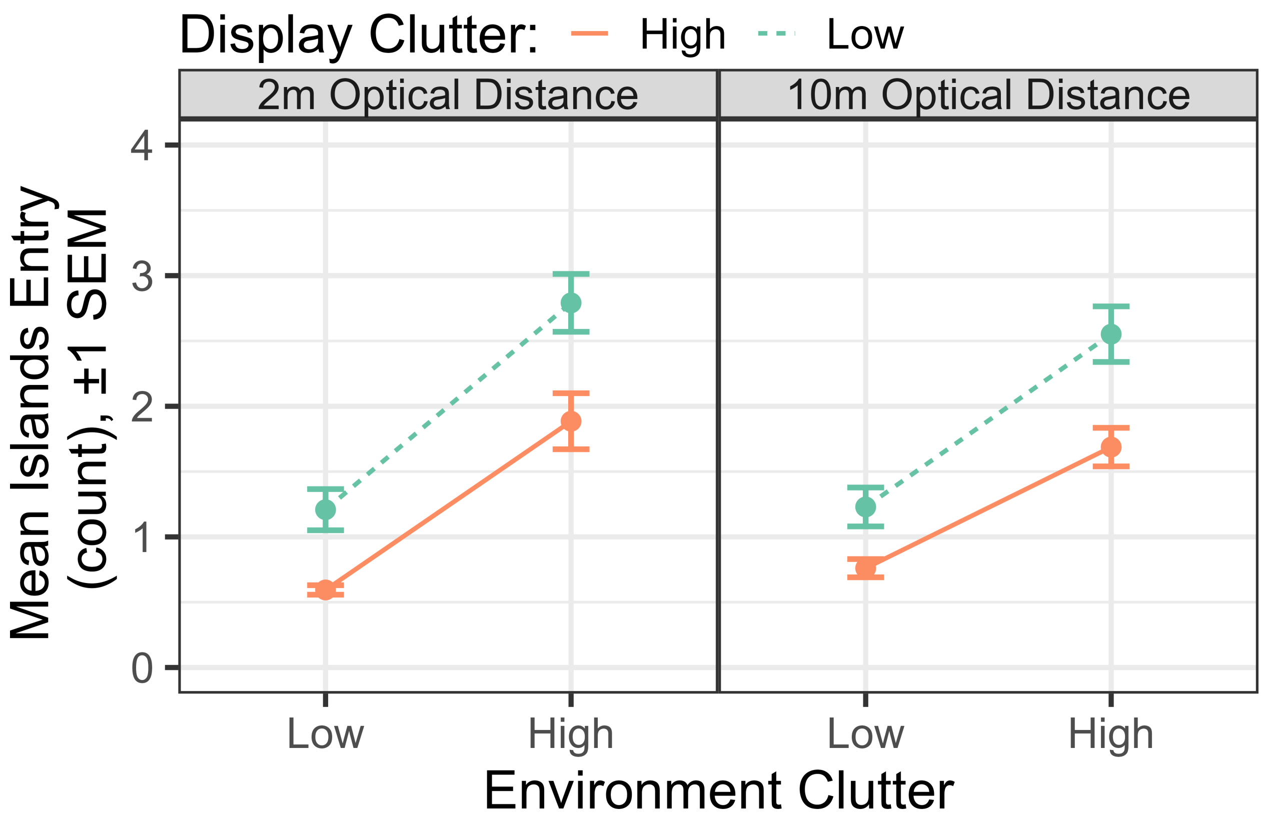


Figure 4.5: Individual graph for Mean Island Proximity Entry. These values illustrate the differences in hazards relative to the Mean Proximity Entry and were plotted by optical distance, environmental clutter, and display clutter. Error bars represent one standard error of the mean.

Island entry takes the proximity entry data and shows only the island information. The analysis of mean island entry showed a statistically significant main effect of environmental clutter, $(F(1,23) = 147, p < .05, \eta_p^2 = .5)$. Figure 4.5 presents the environment clutter analysis that depicts closer proximity to island hazards when clutter was high and farther proximity to hazards when clutter was low. There was a statistically significant main effect of display clutter, $(F(1,23) = 53.56, p < .05, \eta_p^2 = .22)$. In Figure 4.5, the orange or solid lines show the high display clutter, on average, prompted farther proximity to hazards (greater safety). There was no main effect of optical distance, $(F(1,23) = 0.43, p = 0.5, \eta_p^2 = .0008)$; however, there was a statistically significant two-way interaction between environmental clutter and optical distance ($F(1, 23) = 6.90, p < .05, \eta_p^2 = .01$). This interaction can be seen in Figure 4.5, where it can be seen that increasing environmental clutter (more and smaller islands) has a more detrimental effect when the optical distance is low (2 meters, left panel) and therefore obscures more of the scene, than when it is high (right panel). This difference can be easily seen in Figure 4.1.

Obstacles entry takes the information from the proximity entry data and shows only the obstacle information (the floating debris in the water). The analysis of mean obstacle entry showed no statistically significant results for any of the independent variables. This trend shows that islands were the primary safety violation, with no marginal trends in obstacles.

4.8.4 Horizontal Head Deviation

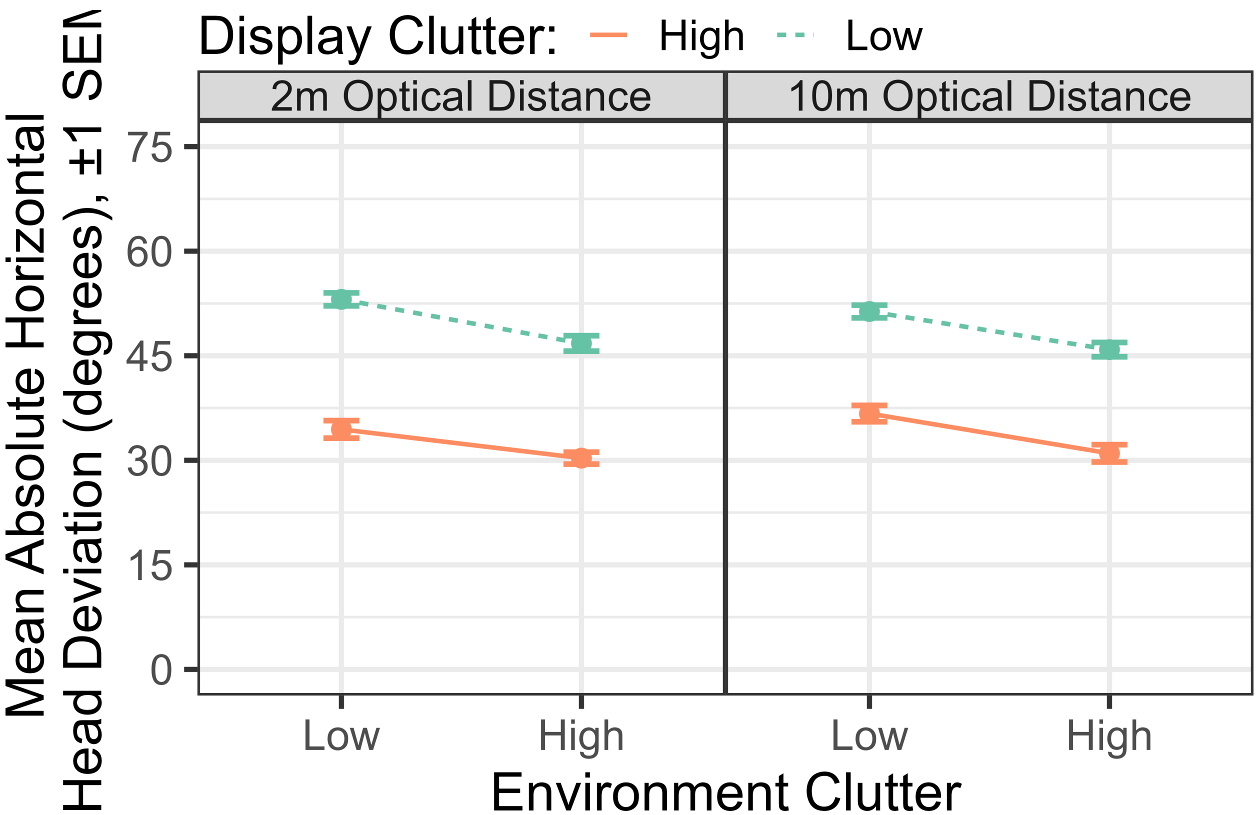


Figure 4.6: Mean of Absolute Horizontal Deviation. These values are then plotted according to the optical distance, environment clutter, and display clutter. Error bars represent one standard error of the mean.

Horizontal Deviation was measured in degrees and is the absolute horizontal gaze excursion of the participants from the nose of the boat. Zero is the boat nose and increases whether looking left or right. The analysis showed a statistically significant main effect of the display clutter, $(F(1, 23) = 1076.26, p < .05, \eta_p^2 = 0.69)$. In Figure 4.6, low display clutter, represented as the green or dotted line, prompted more head rotation regardless of other factors. It also showed a statistically significant main effect of environmental clutter, $(F(1, 23) = 41.39, p < .05, \eta_p^2 = 0.20)$. In each panel of Figure 4.6, high environmental clutter can be seen on the right side of the x-axis and results in lower or fewer head rotations. Lastly, there was no significant main effect of optical distance, $(F(1, 23) = 0.13, p < .7, \eta_p^2 = .0008)$

To summarize our results, we present three tables summarizing the principal significant influences of the three independent variables on efficiency, safety, and horizontal head movement. Table 4.1a and Table 4.1b show the influences for efficiency and Table 4.2 shows the influences for safety. Finally, we present the details of the results for whether they hurt or helped efficiency and safety along with horizontal head movement in Table 4.3.

4.9 Discussion

In the current experiment, we examined three attributes: environment clutter and two HMD properties of optical distance and display clutter. These were assessed for their influence on the performance of a nautical navigation task in terms of efficiency and safety. In addition to the navigational performance, scanning data of the participants were also examined to better understand participants' behavior for each condition. In the following section, we describe the results, their initial impact on navigational efficiency and safety, horizontal scanning behavior, and finish the section with an alternative description of the results. The effects we describe are assumed to be mediated by three information processing variables: an attentional variable related to increased attentional focus on the display interface during route planning, a cognitive variable related to a speed-accuracy tradeoff with the smaller islands, and an attentional/perceptual variable in the transparent display reducing the effects of overlay clutter.

Table 4.1: A summary of the completion time (a) and distance traveled (b) results detailing the ANOVA results for each main effect and interactions between independent variables for efficiency.

(a)

Completion Time Results	**F-Value**	**P-Value**	η_p^2
Environmental Clutter	$(F(1, 23) = 29.85$	$p < 0.05$	0.087
Display Clutter	$(F(1, 23) = 38.42$	$p < 0.05$	0.11
Optical Distance	$(F(1, 23) = 0.25$	$p = 0.6$	0.0007
Environmental Clutter & Display Clutter	$(F(1, 23) = 0.04$	$p = 0.8$	0.0001
Environmental Clutter & Optical Distance	$(F(1, 23) = 0.52$	$p = 0.5$	0.0014
Display Clutter & Optical Distance	$(F(1, 23) = 0.02$	$p = 0.9$	0.00005
Environmental Clutter & Display Clutter & Optical Distance	$(F(1, 23) = 0.17$	$p = 0.7$	0.0005

(b)

Distance Traveled Results	**F-Value**	**P-Value**	η_p^2
Environmental Clutter	$(F(1, 23) = 29.21$	$p < 0.05$	0.13
Display Clutter	$(F(1, 23) = 25.35$	$p < 0.05$	0.15
Optical Distance	$(F(1, 23) = 9.98$	$p = 0.6$	0.04
Environmental Clutter & Display Clutter	$(F(1, 23) = 4.37$	$p < 0.05$	0.01
Environmental Clutter & Optical Distance	$(F(1, 23) = 0.33$	$p = 0.6$	0.001
Display Clutter & Optical Distance	$(F(1, 23) = 0.37$	$p = 0.5$	0.001
Environmental Clutter & Display Clutter & Optical Distance	$(F(1, 23) = 0.87$	$p = 0.36$	0.003

Table 4.2: A summary of the proximity entry of island results detailing the ANOVA results for each main effect and interactions between independent variables for safety.

Proximity Entry of Island Results	F-Value	P-Value	η_p^2
Environmental Clutter	$(F(1,23) = 147$	$p < 0.05$	0.5
Display Clutter	$(F(1,23) = 53.56$	$p < 0.05$	0.22
Optical Distance	$(F(1,23) = 0.43$	$p = 0.52$	0.0008
Environmental Clutter & Display Clutter	$(F(1,23) = 0.02$	$p = 0.9$	0.00006
Environmental Clutter & Optical Distance	$(F(1,23) = 6.9$	$p < 0.05$	0.012
Display Clutter & Optical Distance	$(F(1,23) = 0.67$	$p = 0.4$	0.004
Environmental Clutter & Display Clutter & Optical Distance	$(F(1,23) = 1.0$	$p = 0.33$	0.004

4.9.1 Efficiency

Efficiency was measured in terms of environmental transit time and travel distance. The general trends from our preliminary analysis revealed that the three variables influenced navigational efficiency by increasing attentional focus (possibly even attentional tunneling) on the display interface. The additional effect that the more and smaller islands allowed shorter detours. The additional information (4 additional components in the interface) that was presented in the display interface was all unrelated to the completion of the task; these irrelevant components are: compass, static weather icon, battery level, voice-call icon, and naval code name. This additional information was not useful to navigational performance, but is believed to have helped improve participants' attention to the interface during route planning at the beginning of the trial. This improved the ability to plan a shorter route of travel by making the minimap more salient before moving towards the endpoint buoy, resulting in shorter travel time and completion time. The high environmental clutter had smaller islands compared to low environmental clutter, which had fewer islands but were bigger in shape. These larger island shapes might have caused longer travel times even though there were fewer items in a field of view (fewer islands and hazards).

Table 4.3: A summary of the results detailing if increasing the independent variables helped or hurt efficiency (shorter time and shorter distance), safety (island penetrations), and horizontal head movements.

	Efficiency	**Safety Compromise Island Penetrations**	**Horizontal Head Movements**
Increasing Environment Clutter (More, Smaller, Islands)	Increase (Decrease time, decrease distance traveled)	Increase safety compromise (More penetrations)	Slightly less head movements
Increasing Display Clutter (More irrelevant Features)	Increase (Slightly shorter time, slightly shorter distance)	Decrease safety compromise. (Fewer penetrations)	Reduced head movements
Increasing Optical Distance (Smaller Display obscuring less of the scene)	No Effect	Increasing environmental clutter had a larger safety decrement at close optical distance	No Effect

In our hypothesis H1a, we anticipated that further optical distance, would decrease navigational efficiency, such as increased time and travel distance. After statistical analysis, the opposite was found. Optical distance had little effect on completion time but did have an effect on distance traveled. Decreasing optical distance (2 m) had a significant effect on distance traveled, which prompted shorter travel distance. A potential reason for this is that the 2m distance allowed for more fine discrimination of hazard locations in the display by having an increased visual angle when the participants planned their route to the endpoint.

In our hypothesis H1b, we anticipated that increasing environmental clutter, more islands and obstacles, would decrease navigational efficiency, such as increased time and travel distance. Our statistical analysis found this to be the opposite. Increased environmental clutter prompted faster completion times and shorter travel distances. A possible explanation of this is that the shape of the islands in the high environmental clutter condition potentially provided more gaps in the waterways because the islands are smaller but contained more in the environment. These gaps in waterways might have allowed for straighter pathing to the endpoint.

In our hypothesis H1c, we anticipated that increasing interface clutter, more information in the display, would decrease navigational efficiency, such as increased time and travel distance. Our statistical analysis found this to be the opposite. Increased interface clutter prompted faster completion times and shorter distance traveled. In the current experiment, the display was consistently transparent, which might have reduced the effects of high display clutter similar to Cardenas et al. [35]. A potential reason for this finding is the mini-map that was provided in the UI nearly removed the need to look in the foreground (the environment), making the rest of the display information obsolete. This can be further explored when we include the horizontal head scanning data, which showed that high display clutter led to less head rotation.

4.9.2 Safety

Navigational safety in terms of near collisions with islands and obstacles shows that all three of the variables influenced safety, and our results revealed that near collisions with islands were witnessed rather than near collisions with obstacles. A preliminary analysis revealed that near collisions with islands were imposed by a speed-accuracy tradeoff, and the effect was promoted more with the increased display size (shorter optical distance). Participants were cutting more corners because the smaller islands promoted shorter detours, which led to an increased proximity to islands. This increased proximity to islands is further amplified by the display interface, as the bigger interface created potential occlusions for the scene beyond. Given this pattern, high display clutter should continue this trend of increased proximity to islands; however, our results show the opposite, as high display clutter decreased proximity to islands. The consistent transparent HMD display across all conditions (low opacity display) was transparent enough that the hindrance of obscuring more scene information (high display clutter) was greatly reduced for high display clutter leading to a decrease in proximity to islands.

In our hypothesis H2a, we anticipated that further optical distance, closer depth to hazards, would decrease compromises of navigational safety. After statistical analysis, this was shown to be partially true. Proximity entries to obstacles and both hazards (islands and obstacles) were not statistically significant, but the proximity entry to islands had a two-way interaction between environment and optical distance. A potential reason for this could be that the increased optical distance (10 m) presented the display information closer in depth to the hazards, allowing participants to avoid hazards by being able to notice them more easily by being in a closer depth plane together.

In our hypothesis H2b, we anticipated that increasing environmental clutter, more islands and obstacles, would increase compromises of navigational safety by increasing proximity to hazards. Our statistical analysis strongly confirmed this. More environmental clutter prompted more compromises to safety. To understand this increase in proximity better, both islands and obstacles were examined separately. The statistical analysis did not show any significance for obstacles but did show significance for islands. This points to islands leading to increased compromises of navigational safety rather than obstacles. A potential reason for this could be participants trying to "cut corners" in the high environmental clutter condition by getting closer to the islands to allow for more efficient navigation.

In our hypothesis H2c, we anticipated that increasing interface clutter, more information in the display, would increase compromises of navigational safety by increasing proximity to hazards. Our statistical analysis found this to be the opposite. More interface clutter led to safer navigation and fewer compromises to safety boundary penetrations with islands. A potential explanation for this is that once participants saw the high-clutter interface, it increased their attention to the display and improved their focus on the mini-map while trying to ignore everything else. The low-clutter interface potentially allowed them to look around the environment more (as indicated by low interface clutter having more horizontal head rotation) and led to more accidental compromises while searching.

4.9.3 Horizontal Head Deviation

In our hypothesis H3a, we anticipated that increased optical distance would decrease head rotation. We did not find a significant effect of optical distance on head rotation. A potential explanation for this is that, regardless of where the interface was presented, the participants focused mainly on task-related elements of the interface (mini-map, compass, speedometer) and did not need to search around the environment.

In our hypothesis H3b, we anticipated that increased clutter in the environment would increase head rotation or scanning. We found the opposite in our analysis. More environmental clutter led to less head rotation. One reason for this finding is that the smaller islands in the high environmental clutter condition required less head rotation to complete the task than the larger islands in the low environmental clutter condition.

In our hypothesis H3c, we anticipated that increased clutter in the interface would increase head rotation or scanning. We found this to be the opposite; high interface clutter led to less head rotation. A reason behind this could be that the low-clutter interface could have prompted participants to look around the scene, with more space and freedom to do so.

4.10 Overall Discussion of Experiment 2

To finish the discussion of Experiment 2, we present an alternative description of the results by looking at how the independent variables affected performance. This section uses cognitive mechanisms to explain our findings in environmental clutter, display clutter, and optical distance.

Environmental clutter manipulated the number of islands and floating hazards. To achieve high environmental clutter, the size of the islands was changed to be smaller and contain more islands in total, 20, compared to the low environmental clutter that had bigger islands but fewer islands in total, 10. Performance was affected differently by environmental clutter compared to prior studies and to our hypothesis H1B. These prior studies found that increased environmental clutter resulted in negative effects due to disrupting some level of perception of the display information [21, 22, 32, 50]. In the current experiment, we found that higher environmental clutter did not affect performance in a perceptual way but rather in a navigational strategy way. We believe that these more and smaller islands provided more gaps in the waterways, which allowed for a navigational path to be chosen that was straighter, leading to shorter distance traveled and time taken. Essentially, a more efficient strategic performance was chosen in the highly cluttered conditions; however, this was not the only effect of that choice. This straighter pathing strategy was inferred to lead to more "corner cutting," meaning that more hazard proximity to islands was encountered with the higher clutter imposed by more islands. This strategy increased the likelihood of safety-compromising penetrations into the safety boundaries of the islands.

Display clutter was manipulated by increasing the number of components in the HMD interface. Low display clutter was achieved by using four components in the HMD interface that provided information relevant to completing the task: speed, distance to the target, compass heading, and particularly the mini-map. High display clutter was achieved by using the four components in the low display clutter interface and adding four additional components to the interface that were unrelated to the completion of the task: static weather icon, battery level, voice-call icon, and naval code name. Performance was affected by display clutter in a completely different way than prior studies. Prior work found that increasing display clutter resulted in many negative effects, like performance cost to processing far-domain information as near-domain clutter increased [21, 22], increased response time when scanning [21, 42], and more [18, 26, 57]. In the current experiment, we found that high display clutter did not hurt task performance; in fact, we found that it might have helped task performance by prompting shorter travel distance, faster completion time, and decreased near collisions with hazards. As we mentioned previously, the additional four components in the high display clutter condition had no relevance to the task. This means that it is not the usage of the component that might have helped task performance, but instead we believe that the additional components brought more attention to the display, causing longer scans of the display, specifically to the mini-map component. This increase in attentional focus helped create a more efficient and usable representation of the route in the 2D map to enable not only a more effective route but also to evaluate the route for safety boundaries with the islands. Essentially, safety could be preserved, and a more efficient route could be planned by inspecting the 2D map more than the 3D rendered surrounding scene.

Chapter 6 in the Engineering Psychology and Human Performance textbook [58] has shown that when making precise judgments of distances, which is necessary for navigational planning, 3D egocentric displays are inadequate compared to 2D co-planar displays. 3D displays suffer from a perceptual problem called Line of Sight (LOS) Ambiguity, where height might get confused with distance, causing inaccurate perception, especially when the task requires precise spatial judgments [58]. The ambiguity from 3D displays is eliminated when using 2D top-down display maps because they maintain a consistent scale across all parts of the display compared to the 3D displays that change scaling as it goes towards the "depth" axis [58]. In the current experimental paradigm, the minimap on the HMD interface represented a 2D display map, and the virtual environment of the surrounding scene represented an egocentric 3D display. By increasing the display clutter in the HMD interface, it brought more attention to the 2D map rather than the 3D rendered scene, and the consistent scale of the whole map allowed for better precision in planning the route to the endpoint target. This reasoning follows a similar trend to Wickens et al. [59], who found that using a top-down, north-up mini-map, significantly benefited task performance by reducing response time and improving accuracy, relative to simply relying upon a 3D scene to make precise spatial judgments. In the current experiment, we used a similar top-down, north-up mini-map in the HMD interface display to aid navigation to the endpoint buoy and avoid near collisions with islands, which is a key reason the negative influence of any particular obscuration of the higher clutter would be mitigated. In addition, our reasoning follows similar findings to Chirag et al. [60], who found that detection of their mid-air targets was better with high environmental clutter, which they attribute to an attentional effect. In their study, mid-air targets located below the horizon were presented against a cluttered terrain background, potentially making them more difficult to locate. They believe that the high environmental clutter encouraged more attention to the cluttered terrain because participants recognized that targets in this clutter would be harder to detect, thus strategically directed more attention towards these targets. As a result of the increased attention, it helped target detection of the high environmental clutter mid-air targets. This follows a similar trend to our current experiment, which found that increased display clutter potentially increased attentional focus on the HMD display, which helped improve the usage of the minimap component.

Chapter 5

General Discussion

Both Experiment 1 [35] and Experiment 2 investigated the effects of clutter and HMD properties in a nautical navigation task via two conducted experiments. In this chapter, we highlight the emerging similarities from the results of Experiment 2 and Experiment 1 by Cardenas et al. [35]. The results of these experiments did not substantially differ, pointing to shared conclusions and replicability, despite some of the differences in the independent variables. Across both experiments, we examined four features: (1) environmental clutter, (2) HMD display clutter, and two HMD properties of (3) optical distance and (4) transparency. Environmental clutter was manipulated in Experiment 1 by changing the number of islands, and was additionally manipulated in Experiment 2 by also changing the number of floating obstacles in the water. HMD transparency was manipulated in Experiment 1 by changing between a more opaque interface and a more transparent interface but remained consistently transparent in Experiment 2. Finally, HMD optical distance was not manipulated in Experiment 1 by remaining at a 2-meter distance but was manipulated in Experiment 2 by changing distance from 2-meter and 10-meter distance. Display clutter was manipulated in Experiments 1 and 2 by changing the number of components in the HMD display interface. The HMD interface was also manipulated by being world-reference (static and maintained forward visibility) in Experiment 1 with a cloudy white background and being screen-referenced (follows participant's head movement) in Experiment 2 with a dark background.

5.1 Common Results

Across both experiments, we see a trend of increased environmental clutter leading to significantly faster completion times. To further push this trend, Experiment 2 shows that increased environmental clutter prompted shorter distance traveled. This raises a very interesting question of "why did increased environmental clutter not appear to degrade task performance of efficiency?" In Experiment 1, we believed that the visibility of the islands in the high environmental clutter gave participants confidence to travel at higher speeds, as can be seen in Figure 3.5. In Experiment 2, we reasoned that the high environmental clutter had more gaps in the waterways that allowed participants to find a straighter path towards the endpoint, and they did by having shorter distances traveled, which can be seen in Figure 4.4. From these, we conclude that high environmental clutter created some type of strategic change in how they accomplished the navigation performance task when it comes to island hazards.

Additionally, in both experiments, it was found that the majority of near collisions with hazards came from islands, meaning that near collisions with floating obstacles were practically eliminated despite the doubling of the number of floating obstacles in Experiment 2. To continue the discussion of near collisions, a trend found in both experiments is that increased environmental clutter led to significantly more near collisions with islands. The increase in environmental clutter, specifically the island setup and the island safety boundaries, created more safety boundaries to be aware of and to potentially avoid. Combining the increase in safety boundaries with the improved navigational performance led us to conclude that high environmental clutter might point to corners being cut as part of that strategic change when accomplishing the navigational safety tasks.

In Experiment 2, the display interface was always transparent (partial occlusion), and in the transparency condition of Experiment 1, both experiments revealed that higher display clutter led to fewer safety violations with islands. A potential explanation is that a transparent display with high display clutter increased attentional focus on the display, which improved how participants utilized the minimap, allowing for a better understanding of the safety boundaries with the island hazards. We discuss this as follows. The minimap provided a 2D top-down representation of the virtual environment and this provided more precise judgments of distance compared to the 3D representation that was rendered surrounding them [58, 61]. The 2D map allowed for better planning, allowing for optimal route choice, because distances between islands and judgments of what route to take were unambiguous compared to the 3D rendered environment surrounding them. This precision with the 2D map combined with the increased attentional focus from the highly cluttered display helped participants find the minimap and focus on it to plan better routes that were safer in not violating the safety boundaries of the islands.

5.2 Different Results

Across both experiments, we see similar trends of increased display clutter improving navigational safety; however, this trend is not seen when it comes to navigational efficiency with increased display clutter. In the transparent display condition of Experiment 1, meaning that the display interface only partially occluded the environment, the results of completion time showed that display clutter did not have a significant impact on the time it took to reach the endpoint (Figure 3.5). We reasoned that the transparent display potentially mitigated the effects of high display clutter, as Experiment 1 showed that the opaque display significantly slowed completion time, and that this effect was not seen for the transparent display, which can be seen on the left side of Figure 3.5. This is not the case in Experiment 2. In Experiment 2, which always had a transparent display, there were significant trends ($p < 0.05$) that high display clutter led to faster completion time (Figure 4.3) and shorter distance traveled (Figure 4.4). We reasoned that the increase in display clutter evoked additional attentional focus on the display, improving the 2D minimap's ability to plan for optimal routes to reach the endpoint faster because of the unambiguous judgment of distance compared to the 3D rendered surrounding environment.

In addition to our reasoning above, we also believe that the screen-referenced setup of the interface in Experiment 2, compared to the world-referenced setup of the interface in Experiment 1, potentially made it easier to use the interface. Experiment 1 had the HMD interface always maintaining forward visibility aligned with the nose of the boat, allowing participants to view the 3D rendered environment without the interface. This means that in order to use the 2D minimap or the interface as a whole, the participant would need to glance back to the center of the boat to make navigational changes with the minimap. This need to rotate head movement to glance back at the interface potentially reduced how quickly they were able to utilize the 2D minimap on the interface for navigational efficiency, as they had to readjust to the minimap to figure out the way they were traveling [58]. When looking at Experiment 2, the HMD interface always followed head movements, meaning that it constantly maintained the center of the participant's field of view, allowing participants to utilize the 2D minimap no matter the direction they were looking. By having the HMD interface constantly in view, it might have made it easier to use the minimap as they never had to readjust to the map and could continuously track how they were navigating to the endpoint.

Chapter 6

Limitations and Future Work

One limitation of Experiment 1 was that the design of the environment, and particularly that the floating objects were easily avoidable, as their safety zones were never penetrated, and hence, floating hazard safety was not influenced by any of the independent variables. In Experiment 2, we believed that changing the number of floating hazards with the environmental clutter would create better hazards. This did not appear to be the case, as, in a similar manner as in Experiment 1, the safety zones were never penetrated. A continued limitation, despite changing the frequency of floating hazards, is that the floating hazards were always expected to be in the water and were visible in the minimap. This is different than something like runway incursions used in aviation HUD research [33, 62] as these incursions are unexpected compared to our current paradigm, and unexpected events are more likely to suffer from the harmful effects of clutter. Another limitation is the absence of eye movement data to assess the degree of use of various display elements and hence the extent to which these could be defined as necessary clutter. In Experiment 2, we collected head tracking data that provided insight into hazard detection and scanning behavior, but did not provide information about the HMD display and the use of the different components in the display. Another constraint on this research, also to be addressed in future experiments, is that we did not consider three other UI design factors, all deemed to be important in assessing the desired properties of HMDs for transportation systems:

- The similarity in hue between displayed information and the dominant elements in the scene [42]. For example, the perception of green imagery rendered by an HMD would be expected to be degraded when viewed against a blue-green seascape beyond.
- A future study might explore designing the HMD interface and symbology to allow users to rely solely on the symbology, contrasting this with a condition where users engage in strategic decision-making to identify the optimal path.

- A constant visual angle across optical distance conditions would ensure that HMD information remains highly legible regardless of depth. This could help the farther optical distance HMD interface retain more legibility. But also, reduce attention switching time between the two domains with the trade of promoting the occlusion of the scene by occupying more space.

Chapter 7

Conclusion

This experiment investigated nautical navigation performance when changing display opacity, display optical distance and the amount of clutter in both domains (HMD interface and environment). The task was evaluated in terms of efficiency, safety, mental demand and horizontal head deviation. The results of the study suggest to system designers preliminary guidance on reducing display clutter and using more transparent display designs in high-cluttered environments. It additionally suggests adjusting optical distance to occupy less space but retain high legibility. However, this guidance is speculative as the study looked at one level of display transparency and one level of optical distance for reducing clutter and requires further examination in providing effective HMD display feature design. Overall, the results show promise for the adaptation of HMDs in transportation, as the hazard detection rate was high and unaffected by display clutter when making the display somewhat transparent so that full occlusion was not a problem. Furthermore, the map preserved adequate legibility to allow excellent navigational performance.

Key Points:

1. We varied the display clutter, display transparency, and optical distance of a simulated HMD in a nautical navigational task through environments of different clutter level.

2. A transparent HMD feature in high environmental clutter situations increased nautical navigational efficiency in terms of the task completion time and shorter distance traveled with lower mental demand.

3. In a nautical navigational task with an HMD under high environmental and display clutter situations, leading to more hazard proximity and decreased safety, only in opaque conditions.

4. We identified compromises to both safety and efficiency associated with the combination of low display transparency (opaque display) and high display clutter on an HMD navigating a cluttered environment.

5. We identified a speed-accuracy trade-off associated with the combination of high environmental clutter leading to a change in strategy, prompting faster time, shorter distances, but increases in hazard proximity.

6. We identified an increase in attentional focus on the HMD interface associated with the increase in HMD display clutter, leading to improved scanning of the 2D minimap in the display, allowing for better route planning.

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