The Effect of Object Selection and Operator Movement on Situation Awareness in Virtual Reality

by

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Abstract

Virtual reality provides an immersive visual environment that has been used in airborne surveillance tasks. The way in which operators interact with a virtual environment has been seen to influence their situation awareness and physical stress. The present work examines three aspects of interface design within a virtual space: object selection, operator movement, and search method. In two experiments, participants were immersed in a virtual environment and completed a search task and a recall task that mimicked operations seen in airborne surveillance to get measures of situation awareness and physical stress. Additionally, in the second experiment, measures of mental workload were incorporated through a peripheral detection task to examine available cognitive resources. Although all interface designs showed associated advantages and disadvantages, results from the experiments indicated that operator situation awareness and/or physical stress are benefitted by a head-gaze selection method, a teleportation movement, and an origin-based search method. The implications to airborne surveillance and the design of virtual interfaces are discussed.

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1 Chapter: INTRODUCTION

1.1 General Introduction

Applications of immersive 3-dimensional (3D) display systems have been growing due to the ability of virtual reality (VR) platforms to display multiple streams of data in a manner that closely imitates real environments. Virtual reality provides an immersive visual environment and incorporates interfaces that enable users to effectively interact with the virtual environment. The present research is focused on examining how VR interfaces can be used to enhance operator situation awareness (SA) in a real-world task: airborne surveillance.

In current airborne surveillance systems, operators are required to locate objects that exist in 3D space but are presented using a 2D display with a top-down view. These operations often involve multi-manned aerial vehicles where operators sit adjacent each other and gather, process, and disseminate information regarding other objects in the environment (e.g., ground vehicles, aerial objects, etc.). The goal of airborne surveillance tasks is often to identify and track disturbances and threats to friendly aircrafts which therefore requires locating and gaining relevant information regarding all objects in the environment. The nature of these tasks shows the necessity of situation awareness needed by the operators completing the airborne surveillance as they must remain aware of the changing environment and the elements located within it. It has been suggested that operator situation awareness can be supported by replacing 2D displays with VR systems (Haskell & Wickens, 2009).

For optimal performance VR should provide a realistic way for operators to view and interact with objects in 3D space. Virtual reality interfaces are important as they control how an operator moves within the space and how objects are selected or manipulated. The different ways of interacting with objects in an environment are relevant to airborne surveillance tasks as operators are required to locate and remember objects (e.g., aircrafts) both in training protocols and in everyday applied settings. It is therefore of interest to examine how these VR interfaces could provide more efficient ways of locating targets and increasing the situation awareness of operators. However, it is not clear what type of VR interface provides the most effective means for operators to select, move to, and search for objects in virtual space. While immersive VR environments may lead to enhanced situation awareness, it is possible that the features associated with various interface designs may have effects on pilot mental workload and physical stress. The different ways of interacting with the virtual environment has been suggested to induce the possibility of cybersickness (Davis, Nesbitt, & Nalivaiko, 2015); it is therefore of interest to see if the various interface designs may induce unwanted negative physical symptoms in the operator and if this negatively impacts their task completion. The present work examined how operator situation awareness was affected by three aspects of interface design within a virtual space: object selection, operator movement, and search method.

Object selection is a fundamental task required in airborne surveillance, typically done by selecting objects with a mouse or trackball cursor. A common approach to selecting objects in virtual environments has been through a "hand-ray" interface in which operators select objects by making a pointing hand gesture and pressing a toggle button to produce a ray beam. Once the ray beam intersects with the object of interest, the operator makes a button press to make their selection. An alternative to the hand-ray is a "head-gaze" interface through which operators select objects by gazing at the object to produce a halo around them. Once the object of interest has a halo surrounding it, the operator makes a button press to confirm their selection. The hand-ray and head-gaze selection methods are quite different from each other in that the hand-ray selection method requires a pointing gesture from the hand and produces a ray beam, whereas the head-gaze requires the operators gaze and produces a halo. Both methods of selection change how the visual scene is rendered in different ways (e.g., ray beam vs. halo); it is therefore of interest to see if there are any apparent differences to operator performance. Additionally, other techniques of object selection have been developed in the VR industry (i.e., Leap Motion grasp). The Leap Motion grasp technique solves the issue of altering how the visual scene is rendered by only incorporating the virtual image of the hands and fingers in the environment. It allows users to accurately select objects by making a grasping motion above the object they want to select. This tracking technology does bring limitations in that users are not able to select objects that are located distant from them and they require much more physical space outside the VR environment to select objects. The Leap Motion grasp technique was therefore not tested in the present experiment as it does not advantage airborne surveillance tasks. Hand-ray and head-gaze methods of object selection were compared in the present work to examine their influence on situation awareness, mental workload, and physical symptoms.

In virtual reality environments, operators have the capacity to move their own position in relation to the objects. This translational movement provides them with various points of view, and may assist in decision-making (e.g., determining which object to select) and increase awareness of the virtual environment. Accordingly, this work compared two movement methods: a "teleport" method in which users instantaneously move from one location to the next, and a "dashed" method whereby users move toward targets through the rapid succession of still frames. Of primary interest was how these types of movement affected cognitive performance on tasks that measure situation awareness, mental workload, and physical symptoms. The style of route, or path, taken between objects may influence the time it takes to find objects and on the memory of the object locations in a virtual space.

Lastly, “sequential” and “origin-based” methods of searching for objects were investigated as these search methods have been hypothesized to affect the formation of cognitive maps (Weisberg & Newcombe, 2016). Sequential search is the most common in industry applications and refers to a process where operators move directly from one object to the next during their search tasks. Origin-based search refers to a search method in which operators move back to the center of the environment between searches. The formation of cognitive maps has been tied to situation awareness (Beusmans, Aginsky, Harris, & Rensink, 1995) and it is therefore of interest to examine how these different search methods affect mental mapping. The way individuals moved between objects could also impact operator mental workload and physical symptoms, it was therefore also examined in the present work.

1.2 Literature Review

This literature review considers a prevalent model of situation awareness in airborne surveillance and examines how interface design in virtual reality (object selection, operator movement, and search method) has been found to impact two levels of situation awareness. The literature pertaining to mental workload and physical stress and their impact on situation awareness is also examined, as interface design may indirectly influence situation awareness via its effect on operator mental workload and physical stress.

1.2.1 Situation Awareness and Airborne Surveillance

Situation awareness refers to the perception of environmental elements and events with respect to time and space, the comprehension of their meaning, and the projection of their status in the near future (Endsley, 1988). As airborne surveillance requires the detection and tracking of objects within the environment it is obvious that operators must maintain a high level of situation awareness to complete their tasks. Many factors have been hypothesized to contribute to an operator's situation awareness, and therefore a model should be chosen in order to examine how the factors contribute and interact in varying an operator's situation awareness. Ruiz, Viguria, Marinez-de-Dios, and Ollero (2015) examined the effects of immersive displays for building spatial knowledge by having participants supervise a multi unmanned aerial vehicle (UAV) operation and evaluating their situation awareness using the situational awareness global assessment technique (SAGAT) and their workload using the NASA task load index (NASA-TLX). Three different immersive displays were used: a standard monitor, a surround-screen display, and a head-mounted display and it was determined that immersive displays significantly improved the acquired spatial knowledge of the participants. This study that examines the factors that influence airborne surveillance tasks provides evidence that situation awareness, as well as workload and interface design, are factors that contribute to the performance of operators in their everyday tasks and a model should be chosen that encompasses these (Ruiz, Viguria, Marinez-de-Dios & Ollero, 2015).

Of the various models of situation awareness presented in the literature, Endsley's information processing three-level model is the most prevalent to airborne surveillance. According to Endsley, situation awareness can be categorized into three levels: perception (SA Level 1), comprehension (SA Level 2), and projection (SA Level 3). The first level is the most basic stage and refers to the perception of elements in the environment. This level is where the operator first perceives through the senses that some element (e.g. an aircraft) is present in the environment, along with its relevant characteristics (e.g., colour, shape). The second level refers to the synthesis of these elements to form a comprehension of the current environment. This level allows the operator to form a holistic picture of the environment and a comprehension of the relationship between the elements (e.g., the aircraft is a threat and approaching). The third level refers to the extrapolation of information from the previous levels to determine the future states of the environment. This level allows the operator to project the outcome of the situation (e.g., the most favorable course of action to avoid the threat aircraft).

As seen in Figure 1, Endsley incorporates many factors that are hypothesized to affect all three levels of situation awareness. Her construct of situation awareness is broken down to include more general aspects of human cognition, such as information processing, memory structures, physical stress, and mental workload, to highlight the individual differences between operators. Furthermore, the model includes system factors, such as interface design and system capability, to demonstrate the importance of the physical space and system on situation awareness formation. Of primary interest to this research is how the interface design of a virtual environment can affect an operator's situation awareness on an airborne surveillance task. This research secondly is interested in determining if mental workload and physical stress of the operator are correlated to situation awareness formation.

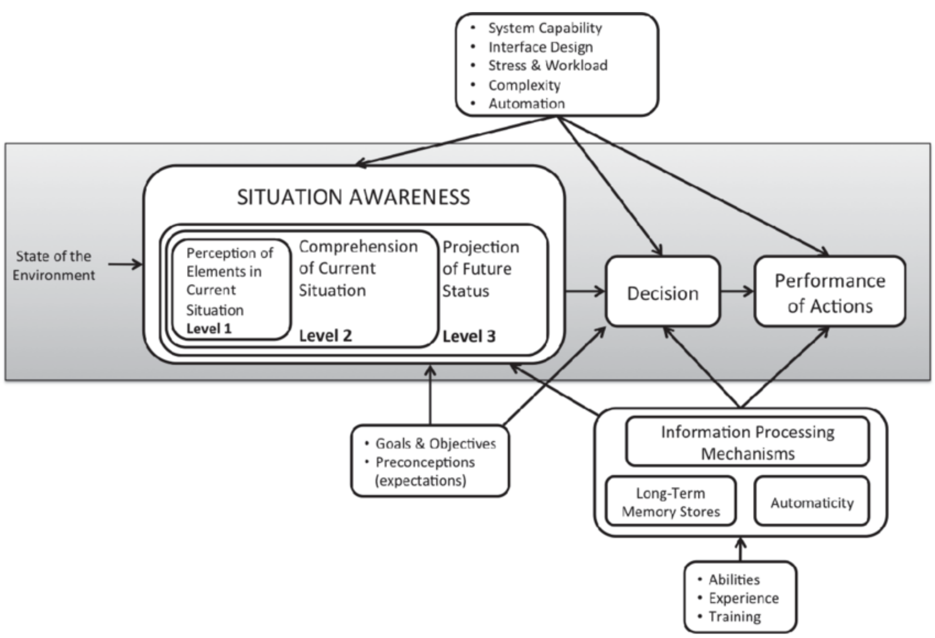

Figure 1: Endsley's model of situation awareness and the three levels of formation

1.2.2 Interface Design on Situation Awareness in Virtual Reality

In accord with Endsley's (1988) model, situation awareness may be influenced by key factors from the environment and features of the task, such as interface design. These factors may differentially affect perception and comprehension of the environment, and thus either help to build or detract from situation awareness formation. Three fundamental interface designs in a virtual environment are considered in the following literature review: object selection, operator movement, and search method.

The way in which an operator selects objects can affect their perception of elements in the environment (SA Level 1) and their comprehension of the relationship between elements (SA Level 2) (Endsley, 1988). To select an object, the operator must detect, identify and comprehend the object's location in the environment. The method that is used to select an object may change how the environment in rendered to the individual (e.g., they must change their gaze direction).

The way in which an operator moves in the environment can also affect the perception of the current state of the environment and the comprehension of relative distances between themselves and the elements. Operator movement may create varying levels of engagement within the environment of change how the scene is rendered as they move (e.g., they see their progression to different locations).

The method in which an operator searches for objects in an environment has also been hypothesized to affect both Level 1 and Level 2 of situation awareness in Endsley's model. Searching for objects in different ways may alter the way an operator interacts with the environment (e.g., they interact with elements in a different order).

1.2.2.1 Object Selection in Virtual Reality

Object selection has been a relatively well-studied area of immersive environment visualization technology (Argelaguet & Andujar, 2012). Object selection is considered an interaction technique that requires a set of selectable objects, a technique to select an object, a mechanism to indicate the time of selection, and a form of sensory feedback (e.g., visual, audible) to inform the operator about a possible or an already performed selection (Steinicke, Ropinski, & Hinrichs, 2006). The common approaches to selecting objects in a virtual environment have been divided between a type of hand-ray selection, in which a ray extends from the operator's virtual hand and strikes the closest object intersection point (ray casting), and a head-gaze selection, in which a halo appears around the object that follows the operator's gaze direction.

First developed by Arthur Appel (1968), the algorithm for ray casting was presented to solve a variety of problems in computer graphics relating to determining the intersection of a ray trace to the closest object blocking its path (Roth, 1982). While conventional applications of the hand-ray selection are ecologically valid as the operator must point to objects, there have been known issues with this interface design. This hand-ray selection method incorporates limb instability and may create difficulties when selecting small distant objects. It also has the added physical constraint of requiring the operator to produce the exact motor movements needed to make a pointing motion (Hinckley, Pausch, Goble, & Kassell, 1994). To assess user feedback on multiple selection techniques, Bowman and Hodges (1997) performed a usability study in a virtual room containing several pieces of furniture. Participants were required to move and rotate furniture and provide qualitative feedback on their experience. The results indicated no clear favorite among the techniques, but that ray casting was never preferred for object manipulation (e.g., rotations, moving objects in and out) due to the fine motor movements required (Bowman & Hodges, 1997). A survey of object selection techniques was also done by Argelaguet and Andujar (2012) whereby they reviewed the major factors that influence selection performance and classified the existing techniques. They suggested that pointing techniques, such as ray casting, introduce new elements to consider, such as the potential modification of the object layout and the way the scene is rendered, as well as issues of occlusion of objects and an altered depth perception (Argelaguet & Andujar, 2012).

To mitigate the issues found in hand-ray selection techniques, a method to select objects based on gaze direction has been proposed as it has been observed that much of the input generated by the hand-ray selection is redundant with the information received by the user's gaze direction (Huckauf & Urbina, 2008). This head-gaze selection method has been hypothesized to afford less complex psychomotor behavior and to be more effective as it allows users more time to precisely select objects of interest. As the head-gaze selection technique is relatively new, there does not exist much experimental research on if these hypothesized advantages are supported. However, Kim, Lee, Jeon, and Kim (2007) proposed various ways for how a head-gaze interface design could improve several psychological factors, including arousing the user's interest and providing enhanced immersion. These improvements were proposed by analyzing user satisfaction after having users interact with the interface through a memory-based board game. They determined that the head-gaze selection increased the user's sense of space and realism but that an increase in user immersion also increased the possibility of inducing VR sickness (Kim, Lee, Jeon, and Kim, 2007). It therefore seems likely that a head gaze selection could improve the perception of the environment, but that it may also cause discomfort. Tanriverdi and Jacob (2000) conducted an experiment to compare gaze selection and point-based selection on performance on a spatial memory task. In the first task, participants were asked to locate two geometrical objects with target letters. The second task was a memory task where they were placed in the same environment and had to recall which two objects contained the target letters from the first task. They found that participants were faster on the first task when using the gaze selection but performed worse on the recall task. An explanation suggested for the speed advantage but recall disadvantage associated with the gaze selection was that the physical burden of interacting with objects was lower and therefore participants spent less time interacting with the objects to retain spatial information (Tanriverdi & Jacob, 2000). The experimental paradigm by Tanriverdi and Jacob was replicated by Cournia, Smith, and Duchowski (2003) to examine search time performance with the distinction that participants did not need to extend their arm to select objects in the point-based selection. There was no clear search time performance advantage of point-based selection over gaze selection unless the objects were distant (Cournia, Smith, and Duchowski, 2003). The result that gaze selection is hindered if objects are further away may be explained by the instability of gaze on small objects; an object located further away will take up a smaller area of the visual field and therefore require a more precise gaze.

Taken together, the studies reviewed in this section provide evidence that both selection techniques afford certain advantages and disadvantages. A hand-ray selection requires more fine motor movements from the operator that decreases user satisfaction but improves spatial recall due to additional time spent interacting with the objects. The hand-ray selection also incorporates the possibility of changing how the scene is rendered due to the ray beam that extends from the hand. Conversely, the head-gaze selection has been found to increase user immersion in a virtual environment but may increase VR sickness. The head-gaze selection has also been found to improve search time performance due to its ease of use, but only if the objects are close enough to not incorporate gaze instability. It appears a tradeoff may be found in which ease of use of the selection method may increase user satisfaction and speed, however will decrease spatial recall. This speed-recall tradeoff is supported by the Atkinson and Shiffrin memory model (1968) in which sensory information that is rehearsed and attended to for longer is stored more permanently in the short-term and long-term memory storage (Atkinson & Shiffrin, 1968). Therefore, although easier and quicker to use, the head-gaze selection may display faster memory decay and lower spatial recall.

1.2.2.2 Operator Movement in Virtual Reality

Operator movement in virtual space has not been as well studied in the literature as object selection but remains an important interface design that should be considered to affect situation awareness. Much of what is known about the different methods of representing an operator's movement has been derived from the gaming industry to enhance user presence (Tamborini & Skalski, 2005). Presence has been said to be improved by a strong match between proprioceptive information from human body movements and sensory feedback from computer generated displays. Slater, Usoh, and Steed (1995) presented research in which they examined the impact of "walking in place" vs. a "pointing method" to move in a virtual environment on user presence. Their results indicated that the subjective rating of presence was enhanced by a stronger match in proprioceptive information and sensory data which was observed in the participants who were able to walk in place to move; however, this sense of presence was also modified by the degree of association of the individual with the virtual body (Slater, Usoh, & Steed, 1995). Mania and Chalmers (2004) examined simulation fidelity and its impact on virtual reality training applications by measuring reported levels of presence and their correlation to memory recall.

They included four different conditions to measure performance on a memory task: real, 3D desktop, 3D head mounted display, and audio-only. They determined that scores for levels of presence and memory recall were statistically higher in the “real” condition, indicating that inducing a high sense of presence is beneficial to memory recall (Mania & Chalmers, 2004). It can therefore be hypothesized that this improved memory recall due to high user presence should be seen in virtual environments as well, and that the way in which operators move in a virtual environment should maximize presence in order to improve situation awareness.

One method of operator movement that has been adopted by several VR games is the teleportation method in which the operator moves instantaneously from one position to another. This method of movement allows users to move vast spaces in a virtual environment with only minimal physical space needed. Linn (2017) compared a gaze teleportation method to a more conventional hand-tracked controller method by getting participants to complete a series of tasks (e.g., moving to different landmarks) and answering a feedback questionnaire. She determined that the gaze teleportation method performed similar to the hand-tracked controller method, but that it surpassed with regards to user preference as it was less visually distracting (Linn, 2017). Another type of teleportation called the “point and teleport” method was investigated by Bozgeyikli, Raij, Katkoori, and Dubey (2016) to compare it to “walk-in-place” and “joystick” locomotion techniques. The results indicated that the teleportation method received positive user feedback and enabled users to move very large or small distances with minimal effort (Bozgeyikli, Raij, & Katkoori, 2016). A known disadvantage of the teleportation method is that it has the potential to disorient the operator as they do not see their path progression from one location to another. A study by Bowman, Koller, and Hodges (1997) examined different techniques for operator movement and their resulting sense of disorientation in the user and performance on a visual search task. The results indicated that infinite velocity techniques (i.e., teleporting) significantly increased user disorientation, led to reduced user presence, and caused participants to be unable to accurately determine target direction (Bowman, Koller, & Hodges, 1997). A possible explanation is that these results are due to the lack of sensation of motion and the inability to build an accurate mental model of their velocity and acceleration.

To address the problem of disorientation, a dashed movement has been developed in certain games in which the operator receives a rapid series of still frames as they progress from one position to another. The possible effects of a dashed movement on situation awareness has not been empirically investigated, however it has the potential advantage of providing the user with optic flow to promote a better understanding of one's orientation within the virtual environment (Redlick, Jenkin, & Harris, 2001). Optic flow refers to the apparent motion of objects in the visual scene that is caused by the relative motion of the observer. The ability to integrate this optic flow information into a multimodal system for assessment of speed and direction of motion is apparent in all humans and can influence situation awareness (Chou, Wagenaar, Saltzman, Giphart, Young, Davidsdottir, & Cronin-Golomb, 2009). The benefit of fluid optic flow was found in a study by Kirschen, Kahana, Sekuler, and Burack (2000) where they examined participants' self-navigation of synthetic environments of virtual corridors and intersections with and without salient optic flow on a path recall task. By varying the rate at which the display was updated, they were able to create either fluid or choppy optic flow and determined that greater accuracy was found in conditions that included fluid optic flow. The presence of choppy optic flow was suggested to interrupt path integration and make it more difficult for participants to put the pieces of the path together (Kirschen, Kahana, Sekuler, & Burack, 2000). Path integration involves updating a mental representation of a place by combining trajectories of previously travelled paths and has been seen to promote faster learning and prevent disorientation. A dashed movement is hypothesized to improve path integration as the operator would receive sensory feedback as they move around the environment and would therefore be able to create a consistent mental representation of the environment based on increased exposure. Conversely, a disadvantage associated with a dashed movement is the possibility of cybersickness due to the visible translational motion and a mismatch between the vestibular and visual systems (Treisman, 1977). The individual perceives motion through the visual system in the virtual environment without any physical movement detected by the vestibular system to cause a feeling of nausea. Davis, Nesbitt, and Nalivaiko (2015) investigated cybersickness that arises in new interface technologies such as the Oculus Rift by comparing the results from two different virtual roller coasters, each with different levels of fidelity, to vary levels of presence. They used a subjective scale to measure the nausea level that participants felt in both conditions. Significant differences were found such that the condition with higher fidelity provided greater levels of optic flow and was more likely to cause the onset of nausea symptoms (Davis, Nesbitt, & Nalivaiko, 2015). Based on the result of higher fidelity and optic flow increasing cybersickness, it seems likely that a dashed movement would increase the discomfort experienced by the operator.

Taken together, research on movement methods in a virtual environment shows that the teleportation movement has received positive user feedback and allows users to move very large or small distances with minimal discomfort; however, it has the disadvantages of disorienting operators as they receive fewer cues for path integration and decreases user presence. Conversely, the dashed movement should increase the operator's sense of orientation due to the information received by optic flow. This dashed movement however has the drawback that the increased user presence could translate into increased discomfort due to cybersickness. It therefore seems necessary that further research must be completed to determine which operator movement affords better situation awareness.

1.2.2.3 Search Method in Virtual Reality

Along with the selection and movement interface designs, the search method afforded to operators in a virtual environment should be considered to influence situation awareness. Search method refers to how operators interact with the environment in order to locate objects and thereby how they form a mental representation of the virtual space (i.e., cognitive map formation). Edward Tolman (1948) first proposed that the brain creates a cognitive map of a spatial environment by deriving the position of an object from reference to at least two other landmarks (Tolman, 1948). In terms of airborne surveillance tasks, it seems likely that operators must create a cognitive map of their environment to determine the current state of the environment and comprehend the relative distances of objects within it by searching and interacting with objects in the environment (Endsley, 1988). Studies done by Weisberg and Newcombe (2016) examined individual differences in effective navigation by testing participants on how well they could learn directions among buildings in a virtual environment. The results proved that individuals with imprecise navigational skills have lower spatial and verbal working memory, and that this may limit their ability to form a hierarchical representation of the environment and build an accurate cognitive map (Weisberg & Newcombe, 2016). The method in which operators search for objects therefore seems likely to affect situation awareness by how operators form these cognitive maps.

Search methods tend to fall into one of two spatial processing strategies: allocentric and egocentric. Allocentric search encodes information about the location of objects with respect to other objects from a stationary reference point; in contrast, egocentric search encodes information about the locations of objects with respect to the self (Klatzky, 1998). With regards to operator search methods in airborne surveillance tasks, two interface designs are prevalent in the literature: sequential and origin-based. Sequential search methods refer to the continuous movement of operators directly from one object to the next; in comparison, origin-based search methods incorporate a central position that operators are moved back to in-between searches. Sequential search methods therefore make use of solely the egocentric spatial processing strategy, whereas origin-based search methods use both allocentric and egocentric spatial processing strategies. It therefore seems necessary to determine whether allocentric spatial processing strategies benefit operator cognitive map formation and if their search tasks are improved by the ability to return to a central position in the environment.

Wolbers and Hegarty (2010) considered three interdependent domains that have been related to navigation abilities: cognitive and perceptual factors, neural information processing, and variability in brain microstructure. They determined that navigation based on cognitive maps requires an understanding of the spatial relationships between important features (e.g., landmarks), and that these relationships can be inferred from a combination of self-movement and the perception of spatial attributes of the environment (Wolbers & Hegarty, 2010). The finding that different factors interact to produce individual patterns of navigational performance suggests that humans use a combination of both allocentric and egocentric spatial processing strategies (i.e., origin-based search method) to form accurate cognitive maps and that tasks that measure situation awareness will benefit from the ability to use both processing systems. When examining different cortical activations in subjects using either an allocentric or egocentric strategy it has been found that activation patterns differ between the two. A paradigm by Chen, Monaco, Bryne, Yan, Henriques, and Crawford (2014) consisted of three tasks with identical stimulus display but different instructions: egocentric reach (remember target location relative to self), allocentric reach (remember target location relative to a visual landmark), and a nonspatial control report (report colour of target). Event-related fMRI data was collected and showed that the egocentric and allocentric tasks elicited widely overlapping regions of cortical activity but with different cortical substrates (Chen, Monaco, Bryne, Yan, Henriques, & Crawford, 2014). Activation of different cortical substrates suggests that both spatial processing strategies may make use of different underlying mechanisms. Another study that examined fMRI images obtained during a task requiring navigation through a virtual 3D environment required participants to use either allocentric or egocentric strategies. Participants using the egocentric strategy used meaningful landmarks (i.e., objects located locally) to navigate the environment, and participants using the allocentric strategy made use of general landmarks (i.e., objects located globally). The results indicated that subjects that used an allocentric strategy showed stronger activation in the medial temporal areas. This memory area activation points to a more automatic support of memory and attentional processes to possibly support the memorization of spatial maps (Jordan, Schadow, Wuestenberg, Heinze, & Jancke, 2004). The different cortical activation seen in both fMRI studies suggests that both spatial processing strategies have different underlying mechanisms, but that the allocentric strategy provides a more substantial memory trace to support situation awareness.

Taken together, the research on search methods in a virtual environment has provided evidence that the method of search that operators use to complete their search tasks influences their cognitive map formation. Furthermore, it seems likely that a search method that makes use of both allocentric and egocentric spatial processing strategies (i.e., origin-based) would improve cognitive map formation due to the ability to use information gained from both self-movement and the perception of spatial attributes in the environment. As both spatial processing strategies have been found to have different patterns of cortical activation, it seems likely that cognitive map formation would also benefit from the ability to use the allocentric spatial processing strategy as it provides the more substantial memory trace. To confirm the previous research, it seems necessary to compare both sequential and origin-based search methods to determine if an allocentric spatial processing strategy benefits operator cognitive map formation, and consequently their situation awareness.

1.2.3 Mental Workload on Situation Awareness in Virtual Reality

As seen previously, situation awareness is affected by not only key environmental factors such as interface design, but also by cognitive factors such as operator mental workload. According to Endsley (1995), situation awareness is reliant on several environmental and cognitive factors that work together to produce updated representations of relevant aspects of the environment; therefore, the operator mental workload associated with the task is of interest to examine its relationship to situation awareness.

Any deleterious effects of high operator mental workload on situation awareness may be presumed to be mediated by concurrent load increases on working memory. As working memory and mental workload are highly correlated, studies examining working memory have been considered. If the demands associated with a task exceed the limited capacity of the working memory of the individual then a decrement in situation awareness is expected (Endsley, 1995). A study by Sohn and Doane (2004) researched the predictive power of working memory capacity and long-term working memory on flight situation awareness in pilots. To assess individual working memory capacity, they used a span task to assess the computation and storage of spatial and verbal information. Long term working memory was tested using a situation recall task where the participants viewed a sequence of two cockpit situations and were asked to recall the situational information. Finally, to assess flight situation awareness they used a query method whereby participants viewed screens that showed a goal description and two consecutive cockpits and made judgement calls (e.g., would the aircraft seen on the screen reach the specific goal state in the next 5 s). The results indicated that working memory capacity was highly correlated with flight situation awareness for novice pilots, and that long-term working memory was highly correlated with flight situation awareness for expert pilots (Sohn & Doane, 2004). It can therefore be suggested that working memory is correlated with situation awareness and that processing a large amount of information with complex demands creates a high working memory load and leads to impaired ability to detect and remember stimuli in an environment.

According to Baddeley's (1974) model of working memory there exists a central executive for processing information which combines a visual-spatial scratchpad and a phonological loop for retaining information suggesting that working memory stores manipulate dynamic information from the environment and any measure of situation awareness must somehow tap into this (Endsley, 1995). It has been suggested that taxing the phonological loop of working memory impairs situation awareness by loading its central executive as proven in a study done by Heenan, Herdman, and Brown (2014). They examined the effect of conversation on situation awareness and working memory on participants in a 20-questions task while in a driving simulator by including three conditions: no conversation, driver answer, and driver ask. Both the driver answer and driver ask conditions were assumed to utilize central executive resources, however more so in the driver ask. They measured the participants' ability to maintain their vehicle speed and lane position and their performance on a peripheral detection task (PDT) where they had to detect a small visual probe at pseudo-random time intervals on the display. Results indicated that the driver answer and driver ask conditions significantly reduced the participants' ability to monitor their speed and respond to the visual probe (Heenan, Herdman, & Brown, 2014). With regards to the present research, the results indicate that taxing working memory stores is highly linked to decreases in situation awareness formation and that any increase in operator mental workload would cause impairments on tasks that rely on situation awareness.

As seen above, mental workload can have a direct effect on situation awareness, however it seems necessary to also examine any factors that could indirectly affect situation awareness via changing the amount of mental workload available. The way in which an interface's design can affect mental workload should be considered as its effects may influence the performance of operators on surveillance tasks. Kaber, Riley, Zhou, and Draper (2000) studied the effect of visual interface design on workload in a teleoperation task where they had participants control a telerobot in a simple pick-and-place task in VR. The interface was varied by including live-video feedback in some of the conditions and changing the latencies of the rotational and translational motion. Results of the study suggested that workload, as measured through NASA-TLX scores, was affected by changing the interface design (Kaber, Riley, Zhou, & Draper, 2000). It therefore seems that interface design can have direct and indirect effects on situation awareness whereby it directly affects the perception and comprehension of the environment, but it also can have effects on mental workload which in turn varies the level of situation awareness of operators.

Taken together, the studies examined above have provided evidence that mental workload as it relates to working memory is a key factor that must be considered when examining situation awareness. Working memory capacities and long-term working memory have been seen to predict flight situation awareness in pilots. Additionally, increasing perceptual loads (e.g., the phonological loop) has been correlated to decreases in working memory capacities and to impairments on tasks that measure situation awareness. It therefore seems of interest in the present work to examine if a correlation appears between mental workload and measures of situation awareness. Finally, interface design has been seen to vary levels of mental workload and should also be examined to see if it has direct and indirect effects on situation awareness.

1.2.4 Physical Stress on Situation Awareness in Virtual Reality

In addition to interface design and mental workload, the physical stress of the operator has been suggested to impact situation awareness on airborne surveillance tasks. Many concerns associated with the application of virtual reality to airborne surveillance tasks have been focused on how operators may feel dizzy, disoriented and/or nauseous while completing tasks in an immersive 3D environment.

Cognitive skills, such as situation awareness, have been known to be susceptible to the effects of work-related conditions such as fatigue and physical stress (Endsley, 1999). For instance, a study presented by Sneddon, Mearns, and Flin (2013) examined the influence of physical stress and fatigue on situation awareness and safety in offshore drilling crews. They developed a self-report questionnaire to collect data on cognitive failures, situation awareness, physical stress, sleep disruption, fatigue, unsafe behavior, and accident history and recorded responses from 378 drilling personnel. Their results indicated that physical stress and fatigue were correlated but the multiple regression analysis showed that physical stress was the only significant predictor of situation awareness (Sneddon, Mearns, & Flin, 2013). This relationship between high physical stress and low levels of situation awareness indicates physical stress should be a measure of impact considered when attempting to improve situation awareness formation in operators on airborne surveillance tasks. A second study examining mental workload and psychophysiological stress reactions in 205 air traffic controllers was conducted by Zeier (2007). The study included one working sessions with a period of low traffic (low mental workload) and one working session with a period of high traffic (high mental workload) and recorded participants' answers to standardized questions to assess physical stress factors, such as physical discomfort. Saliva samples were also collected to assess the concentration of secreted cortisol, also known as the stress hormone. Results indicated that the subjective ratings of air traffic controllers corresponded clearly to their cortisol response and the mental workload condition they were placed in (Zeier, 2007). It therefore seems likely that physical stress and mental workload are tightly coupled and that they together can influence situation awareness formation.

As seen above, physical stress can have a direct effect on situation awareness, however it seems necessary to also examine any factors that could indirectly affect situation awareness via changing the amount of physical stress within the operator. The way in which an interface's design can affect stress levels should be considered as its effects may influence the performance of operators on surveillance tasks. Virtual reality-induced symptoms and effects (VRISE) is a common problem faced by users of head-mounted displays whereby the design of the virtual environment can have negative user experience. A review paper by Cobb, Nichols, Ramsey, and Wilson (2006) examined nine experiments in the literature that studied the effects experienced by participants during and after exposure to various VR systems and designs. They examined not only performance measures to get an indication of physical stress, but also qualitative measures such as self-report scales, user attitude/opinion questionnaires, and interview data. The results indicated that across all experiments the physical stress of the user was affected by the different kinds of interface designs of the VR system (Cobb, Nichols, Ramsey & Wilson, 2006). It therefore seems that interface design can have direct and indirect effects on situation awareness whereby it directly affects the perception and comprehension of the environment, but it also can have effects on the physical stress of the operator which in turn varies the level of situation awareness of operators.

Taken together, the studies that examined the impact of physical stress on mental workload and situation awareness have provided evidence that a correlation exists. High physical stress was seen to be a significant predictor of situation awareness formation and cortisol levels were found to correspond to mental workload conditions. Furthermore, interface design has been seen to vary levels of physical stress and should also be examined to see if it has direct and indirect effects on situation awareness.

1.3 Present Research

The objectives of the present research were to (a) determine if interface design factors within a virtual environment directly affect situation awareness, (b) determine if interface design factors within a virtual environment directly affect physical stress and operator mental workload, and (c) determine the relation of physical stress and mental workload to situation awareness. The present research was done to gain insight on how virtual reality interfaces should be designed to improve airborne surveillance tasks by optimizing situation awareness while minimizing physical stress and the mental workload of the operator. Two experiments are reported.

Experiment 1 tested the association of interface designs with situation awareness and physical stress. Experiment 1 examined key aspects of situation awareness using a task that required participants to select, move to, and remember the locations of entities in a virtual search environment with features that imitated those that might be encountered during airborne surveillance tasks. With regards to airborne surveillance, the tasks chosen were used to assess the perception (SA Level 1) and the comprehension (SA Level 2) of elements in the environment as needed in typical search tasks by operators. Performance was compared across conditions that combined three different interface factors: selection (head vs. ray), movement (teleport vs. dashed), and search method (sequential vs. origin-based). Experiment 1 further examined a self-reported rating scale that required participants to rate their level of discomfort to give an indication of physical stress.

The findings from Experiment 1 were used to refine the tasks for Experiment 2, such that the worst interface feature was eliminated from the experimental design. Several measures of mental workload were also added in Experiment 2. Experiment 2 examined mental workload through a peripheral detection task (PDT) and by measuring peaks in electrodermal activity (EDA) to see how it correlated to the measures of situation awareness and physical stress.

Importantly, Experiment 2 examined performance on the same tasks used in Experiment 1 to permit replication of key findings from Experiment 1. Endsley's model of situation awareness makes predictions regarding the relations between the different levels of situation awareness, and how endogenous factors, such as interface designs and operator mental workload and physical stress might affect each level of situation awareness. Another contribution of this work to investigations of situation awareness in VR environments is the testing of Endsley's model regarding the relationships between situation awareness and VR factors.

2 Chapter: EXPERIMENT 1

Experiment 1 was designed to investigate if the different interface design factors could influence situation awareness and operator physical stress and if a relationship exists between the two outcome variables. Based on Endsley's (1988) model, the methods have been developed to investigate SA Level 1 and SA Level 2. Performance measures on a task that required the perception and comprehension of entities in a virtual environment were used to give a measure of situation awareness. This was done by examining two key tasks that were generated from a visual search task. The first task involved the interrogation of objects and the recording of object information. The second task was a memory activity that required the participants indicate the correct shape and colour of the object in its previous position. Response times (RT) were recorded for both the interrogation and memory tasks, and accuracy (ACC) was also recorded for the memory task. Response time on the interrogation task indexed the perception of entities in the virtual environment, which was associated with SA Level 1 of Endsley's model. Additionally, RT and ACC on the memory task gave an indication of the comprehension of the current environment, which could be associated to SA Level 2 of Endsley's model. A self-report rating scale was used as an index of operator physical stress and a qualitative feedback scale was used to gain user feedback on the various interface designs. Results from the analyses in Experiment 1 were used to eliminate inferior interface factors and refine the analyses for Experiment 2.

2.1 Method

2.1.1 Participants

Twenty-four (n = 24) Carleton University undergraduate students were recruited and tested using the university's online experiment sign-up system. Participants were compensated by receiving $20 at the end of the session. Participation criteria included having normal or corrected-to-normal vision and no diagnosis of colour blindness. The sample included 14 females and 10 males with an average age of 21 years old (*SD* = 6.53).

2.1.2 Equipment and Virtual Environment

An LCD monitor with a 1920 x 1200 resolution was used to render the virtual environment on an Oculus Rift CV1 head-mounted VR display, which tracked participants' head movement such that the environment was always in view. The field of view was approximately 110° vertically and horizontally. A Leap Motion hand tracker was affixed to the front of the Oculus Rift and used infrared (IR) tracking technology to fit a kinematic model to the user's hand in order to track and visually represent hand and finger movements in real time. Input devices consisted of an Oculus Touch controller, which allowed users to select entities by a button press, and a virtual number pad to allow users in input responses. The visuals and user interface were controlled by custom in-house software built on the Unreal gaming engine platform (Version 4.13).

As seen in Figure 2, the virtual environment consisted of land terrain similar to that found in airborne surveillance tasks whereby lakes, mountains, and greenery populated the virtual environment. Local cues were presented in the form of colored land areas (e.g., red rocks) to help participants orient themselves in the environment. Nine entities were randomly dispersed within the environment and were represented as icons crossing three volumetric shapes (pyramid, cube, sphere) with three colors (green, yellow, red). Each entity was labelled with a unique numerical identified (1-9) which was located adjacent to the icon. The size of the entities was scaled according to the distance between the participant's current location and the entity. The task instructions were displayed on a virtual screen that was located on the right side of the virtual environment and maintained a set size and position relative to the participant's current location.

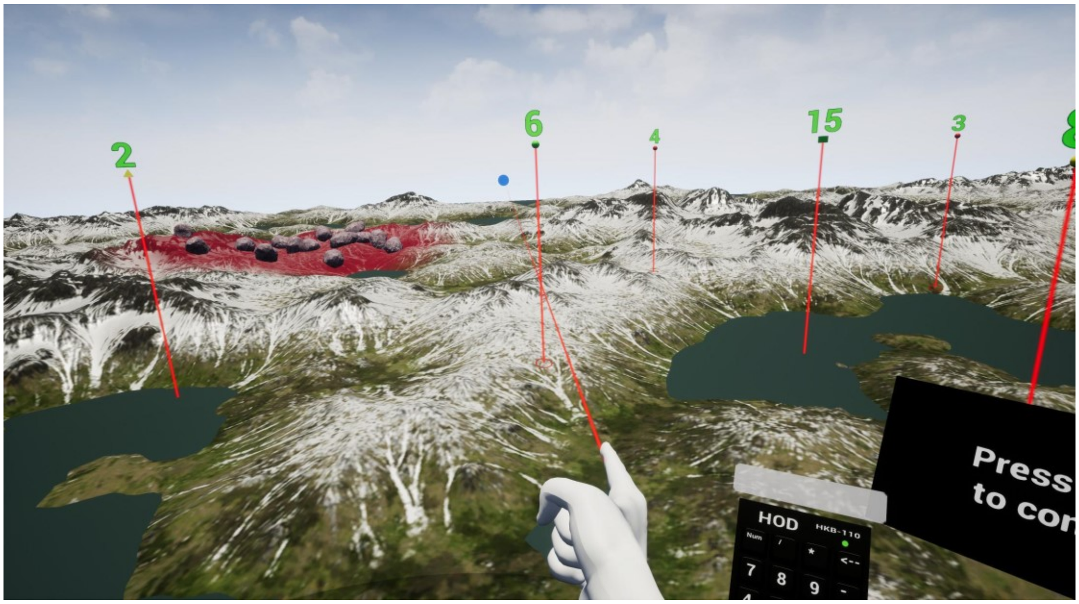

Figure 2: Virtual environment as seen through the Oculus Rift head-mounted display

2.1.3 Design

A 2 (Selection: head, ray) by 2 (Movement: teleport, dashed) by 2 (Search: sequential, origin-based) repeated measures design was conducted. As seen in Table 1, the three interface factors were crossed to create eight unique conditions. Each condition was blocked and counterbalanced across participants following a Latin-Squares design.

Selection: This interface factor referred to how participants selected entities in the virtual environment. There were two levels: Head and Ray. The gaze-based head selection consisted of a crosshairs cursor that is yoked to the participant's head position and was tracked by the Oculus Rift CV1 IR sensors. The cursor appeared where the participant was fixating. The point-based ray selection appeared as a laser beam that extended from the participant's virtual hand in the direction that he/she was pointing. The participants hand motions were tracked using the Oculus Touch.

Movement**:** This interface factor referred to how participants moved towards entities in virtual environment. There were two levels to the factor: Teleport and Dashed. The teleport condition would instantaneously move participants to the entity they selected from their current location. The dashed condition used a rapid succession of still frames as they moved closer to the entity they selected. The dashed movement always took .255 milliseconds from origin to object.

Search: This interface factor referred to the path that the participants followed as they progressed through the virtual environment. There were two levels to the factor: Sequential and Origin-Based. The sequential condition allowed participants to move directly from one entity to another to promote an egocentric spatial processing strategy. The origin-based condition would automatically return participants to a central starting position before they interrogated another entity to promote both egocentric and allocentric spatial processing strategies.

Table 1: Corresponding interface factors for each condition

	Interface Factors		
	Selection	*Movement*	*Search*
Condition 1	Head	Teleport	Sequential
Condition 2	Head	Teleport	Origin-based
Condition 3	Head	Dashed	Sequential
Condition 4	Head	Dashed	Origin-based
Condition 5	Ray	Teleport	Sequential
Condition 6	Ray	Teleport	Origin-based
Condition 7	Ray	Dashed	Sequential
Condition 8	Ray	Dashed	Origin-based

2.1.4 Tasks

Interrogation Task: Participants were presented with instructions asking them to report the latitude or longitude of a numbered entity by entering a 4-digit value on a virtual number pad (See Figure 3). They were required to complete this task nine times interacting with each unique entity once. The purpose of this task was to measure SA Level 1 by requiring the perception of entities in the environment.

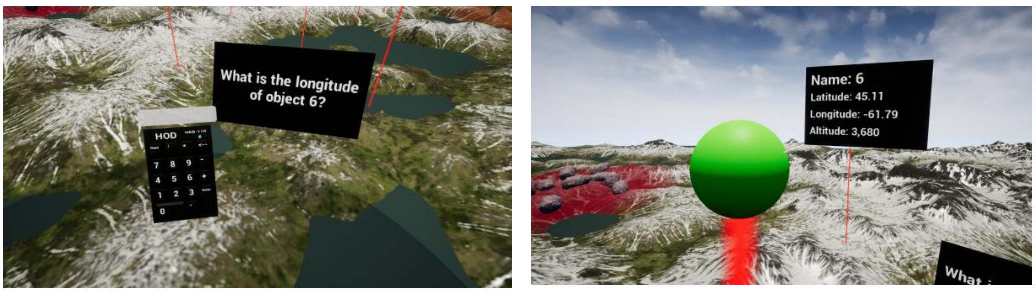

Figure 3: Sample instructions for interrogation task

Memory Task: Participants were placed back in the same search environment as the interrogation task, but with empty placeholders in the locations that were previously occupied by the nine entities. As seen in Figure 4, the participants were required to indicate the correct entity colour and shape as seen from the interrogation task. The purpose of this task was to measure SA Level 2 by evaluating if the participants were able to comprehend the spatial locations and properties of the entities from the interrogation task.

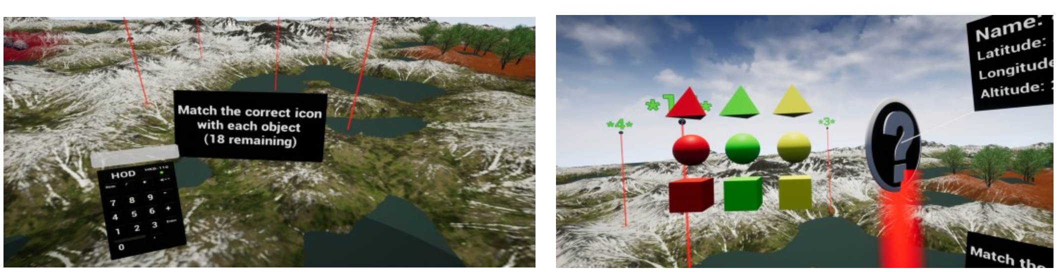

Figure 4: Sample instructions for memory task

2.1.5 Procedure

Participants were tested individually and given an informed consent form to complete. Participants were then given experimental instructions and asked to complete a brief demographics questionnaire. Preparation for the experiment included a 10-minute training phase to familiarize with the VR search environment. Participants then began the first of the eight conditions according to their counterbalance order while wearing the Oculus Rift headset and using the Oculus Touch controllers. Participants were required to complete both the interrogation task and the memory task per condition block. Following each condition block, participants were asked to complete a 6-point Likert scale to indicate their level of discomfort (dizziness, disorientation, and queasiness). At the end of the experiment participants were given a feedback questionnaire, debriefed, and compensated for their time. The entire experiment duration ranged from 90-120 minutes.

2.1.6 Dependent Variables

There were three dependent variables measured: SA Level 1, SA Level 2, and Physical Stress. As seen in Table 2, the associated measures are listed for each dependent variable.

Table 2: Dependent variables and associated measures

Dependent Variable	Measure
SA Level 1	Response Time on Interrogation Task (SA Level 1 RT)
SA Level 2	Response Time on Memory Task (SA Level 1 RT)
	Accuracy on Memory Task (SA Level 2 ACC)
Physical Stress	Scores on three Likert scales (Discomfort Rating [dizziness, queasiness, and disorientation])

SA Level 1: This dependent variable was measured by recording the response time on the interrogation task per condition. It was measured from the time participants were presented their first interrogation trial to when they submitted their answer to the ninth interrogation trial.

SA Level 2: This dependent variable was measured in two different ways: response time and accuracy on the memory task per condition. The response time was measured from the time participants were presented their first memory trial to when they submitted their answer to the ninth memory trial. The accuracy was measured as the amount of features they remembered correctly about the entities. Each entity had an associated shape (1 point) and colour (1 point) and if the participants remembered both they were awarded a score of 2. There were 18 entities per condition, therefore participants scored between 0-36.

Physical Stress: This dependent variable was measured by recording the discomfort rating submitted on a 6-point Likert scale per condition. The discomfort rating was scored between 0-18 by summing the participant responses to three indices: dizziness, queasiness, and disorientation.

2.2 Hypotheses

Endsley's model provided a platform for disambiguating the impact of virtual reality interface design on situation awareness and how it can influence the physical stress of the operator. Thus, as well as looking for the main effects of the interface factors on SA Level 1 and SA Level 2, correlations between the different indices of situation awareness were also examined (SA Level 1 RT, SA Level 2 RT, SA Level 2 ACC), and if physical stress (Discomfort Rating) yielded any relationship to situation awareness.

Interface Design on Situation Awareness and Physical Stress

Table 3: Summary of hypothesized best interface design

Dependent Variable	Hypothesized Best Interface		
	Selection	**Movement**	**Search**
1.SA Level 1 RT - Interrogation Task	Head (Hypothesis 1A)	Dashed (Hypothesis 1B)	Origin-Based (Hypothesis 1C)
2.SA Level 2 RT - Memory Task	Head (Hypothesis 2A)	Dashed (Hypothesis 2B)	Origin-Based (Hypothesis 2C)
3.SA Level 2 ACC - Memory Task	Head (Hypothesis 3A)	Dashed (Hypothesis 3B)	Origin-Based (Hypothesis 3C)
4.Physical Stress - Discomfort Rating	Head (Hypothesis 4A)	Dashed (Hypothesis 4B)	Origin-Based (Hypothesis 4C)

Hypothesis 1-4A: Head selection, as compared to ray selection, will result in better SA Level 1 and SA Level 2 due to the ability of selecting objects without complex hand movements and a lower amount of modification to the visual scene. Head selection will also result in lower physical stress due to decreased psychomotor processing needed to make complex hand movements.

Hypothesis 1-4B: Dashed movement, as compared to teleport movement, will result in better SA Level 1 and SA Level 2 due to the integration of optic flow information. Dashed movement will also result lower physical stress due to the disorientation associated with an instantaneous movement.

Hypothesis 1-4C: Origin-based search, as compared to sequential search, will result in better SA Level 1 and SA Level 2 due to the ability to combine both allocentric and egocentric spatial processing strategies. Origin-based search will also result in lower physical stress due to a constant cognitive map of the environment that lowers disorientation.

Correlation Analysis of Grand Total Measures

Table 4: Summary of hypothesized correlations of grand total measures

Dependent Variable	Hypothesized Correlations		
	1	**2**	**3**
1.SA Level 1 RT - Interrogation Task	--		
2.SA Level 2 RT - Memory Task	Positive (Hypothesis 1D)	--	
3.SA Level 2 ACC - Memory Task	Negative (Hypothesis 1E)	Negative (Hypothesis 2D)	--
4.Physical Stress - Discomfort Rating	Positive (Hypothesis 1F)	Positive (Hypothesis 2E)	Negative (Hypothesis 3D)

Hypothesis 1D: SA Level 1 will be positively correlated with SA Level 2 RT. Participants who perceive the environment quickly will be faster to remember it.

Hypothesis 1E: SA Level 1 will be negatively correlated with SA Level 2 ACC. Participants who perceive the environment quickly will be more accurate in remembering it.

Hypothesis 1F: SA Level 1 will be positively correlated with Physical Stress. Participants who perceive the environment quickly will be less discomforted.

Hypothesis 2D: SA Level 2 RT will be negatively correlated with SA Level 2 ACC. Participants who remember the environment quickly will be more accurate in remembering it.

Hypothesis 2E: SA Level 2 RT will be positively correlated with Physical Stress. Participants who remember the environment quickly will be less discomforted.

Hypothesis 3D: SA Level 2 ACC will be negatively correlated with Physical Stress. Participants who are more accurate in remembering the environment will be less discomforted.

2.3 Results

A 2 (Selection: head, ray) by 2 (Movement: teleport, dashed) by 2 (Search: sequential, origin-based) ANOVA with all factors as repeated measures was conducted for each of the measures. Interactions between the factors were examined, if present, as a method for determining the best grouping of interface design features. For example, a ray-based selection might be beneficial, but only when combined with a specific search and movement. Separate tests showed that there were no significant overall effects of counterbalance detected for any of the measures. If not discussed, the data was normally distributed and free from outliers. Outliers were tested for any effects on the statistical results (by comparing test results with and without the outliers) and were not removed if the effects were not altered by the outlier values. Tests of sphericity were conducted for the counterbalance tests, and Greenhouse-Geisser values were considered when the assumptions were not met. Because a repeated measures design was used, all marginal main or interaction effects, as per the F-statistic ($p < .1$ and $p > .05$), were examined using the confidence interval tests as recommended by Holland and Jarmasz (2009). As recommended by Cohen, the size of the effect was also evaluated using partial eta squared values, where 0.01 was small, 0.09 was medium, and 0.25 was considered large (Cohen, 1988). Finally, to elicit any possible pattern of interface effects the fastest response times (RT), highest accuracy (ACC), and lowest physical discomfort results were highlighted for each analysis.

SA Level 1

Perception of the environment (SA Level 1) was indexed by examining the RT for the entity interrogation task. As shown in Table 5, the fastest overall RT was found in condition 1, with the head-teleport-sequential combination of interface factors.

Table 5: Mean RT in interrogation task per condition

	RT	
	M	*SD*
Condition 1 (head teleport sequential)	**127.25**	**42.60**
Condition 2 (head teleport origin)	145.37	42.17
Condition 3 (head dashed sequential)	146.74	44.37
Condition 4 (head dashed origin)	143.85	37.30
Condition 5 (ray teleport sequential)	151.34	44.45
Condition 6 (ray teleport origin)	150.32	42.69
Condition 7 (ray dashed sequential)	136.36	39.23
Condition 8 (ray dashed origin)	141.63	38.71

Note. The bolded text highlights the condition with the fastest RT during the interrogation task.

As seen in Table 6, there were no significant main effects of selection or movement on RT in the interrogation task. There was a marginal effect of search on RT, such that the fastest RT (less than 140 seconds) was found in the sequential search condition. As seen in Figure 5, this marginal effect of search was examined using Holland and Jarmasz (2009) suggested confidence intervals to indicate that it was driven by the head-teleport combination of interface designs. There was a marginal two-way interaction (medium effect size) for selection by movement, such that the head selection was associated with faster RT with the teleport movement, but the ray selection was associated with faster RT with the dashed movement. As seen in Figure 5, confidence intervals indicate that it was driven by the sequential search condition. It can therefore be proposed that sequential search makes the interaction effects of selection by movement more apparent. The two-way interactions of selection and movement by search were non-significant. There was a significant three-way interaction between all three factors where selection interacted with movement, but only for the sequential search method. As illustrated in Figure 5, in the sequential condition the teleport movement method resulted in the fastest RT when paired with the head selection method (condition 1). This contrasts with the faster RT for the dashed movement when paired with the ray-based method of selection. There were no obvious advantages of either movement or selection in the origin-based condition.

Table 6: Tests of main effects and interactions on SA Level 1 RT

Variable	$F(1, 23)$	p	η_p^2
Selection	.866	.362	.036
Movement	.212	.650	.009
Search	**4.172**	**.053**	**.154**
Selection X Movement	**4.096**	**.055**	**.151**
Selection X Search	.606	.444	.026
Movement X Search	1.922	.179	.077
Selection X Movement X Search	**5.741**	**.025**	**.200**

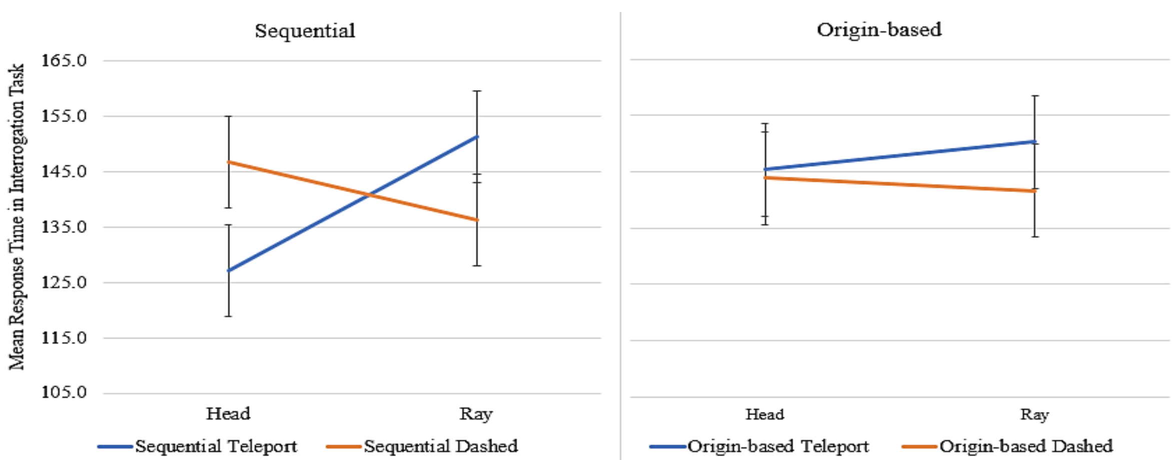

Figure 5: Mean RT in interrogation task by selection and movement per search.

2.3.1 SA Level 2

Comprehension of the environment (SA Level 2) was indexed by RT and ACC on the entity memory task.

2.3.1.1 SA Level 2 Response Time

The analysis revealed one significant outlier that was due to a recording error; this was therefore excluded from the analysis entirely. Tests for normality indicated that the data was not normally distributed; therefore, the data was log transformed before running the analysis. As shown in Table 7, the fastest RT was found in condition 2, with the head-teleport-origin combination of interface factors.

Table 7: Mean RT in memory task per condition

	RT	
	M	*SD*
Condition 1 (head teleport sequential)	85.92	35.83
Condition 2 (head teleport origin)	**75.34**	**27.52**
Condition 3 (head dashed sequential)	81.32	28.74
Condition 4 (head dashed origin)	85.99	31.79
Condition 5 (ray teleport sequential)	86.67	35.06
Condition 6 (ray teleport origin)	84.78	25.08
Condition 7 (ray dashed sequential)	85.04	28.71
Condition 8 (ray dashed origin)	84.16	32.46

Note. The bolded text highlights the condition with the fastest RT during the memory task.

As seen in Table 8, there were no significant main effects of selection, movement, or search on the RT in the memory task. All interactions were non-significant.

Table 8: Tests of main effects and interactions on SA Level 2 RT

Variable	$F(1, 22)$	p	η_p^2
Selection	.980	.333	.043
Movement	.293	.594	.013
Search	.243	.627	.011
Selection X Movement	.471	.500	.021
Selection X Search	.045	.835	.002
Movement X Search	.986	.331	.043
Selection X Movement X Search	2.599	.121	.106

2.3.1.2 SA Level 2 Accuracy

As shown in Table 9, the highest ACC was found in condition 4, with the head-dashed-origin combination of interface factors.

Table 9: Mean ACC in memory task per condition

	ACC	
	M	*SD*
Condition 1 (head teleport sequential)	9.75	3.15
Condition 2 (head teleport origin)	9.79	3.70
Condition 3 (head dashed sequential)	9.71	3.39
Condition 4 (head dashed origin)	**10.83**	**3.77**
Condition 5 (ray teleport sequential)	9.50	3.19
Condition 6 (ray teleport origin)	10.29	3.39
Condition 7 (ray dashed sequential)	9.71	3.54
Condition 8 (ray dashed origin)	10.29	3.24

Note. The bolded text highlights the condition with the highest ACC on the memory task.

As seen in Table 10, there were no significant main effects of selection or movement on ACC for the memory task. A marginal main effect of search was found such that the origin-based search showed higher ACC as compared to the sequential search. As illustrated by the confidence intervals in Figure 6, the effect of search may be driven by the head-dashed combination of interface designs. All interactions were non-significant.

Table 10: Tests of main effects and interactions on SA Level 2 ACC

Variable	$F(1, 23)$	p	η_p^2
Selection	.027	.870	.001
Movement	.349	.561	.015
Search	**3.053**	**.094**	**.117**
Selection X Movement	.177	.678	.008
Selection X Search	.018	.893	.001
Movement X Search	.270	.608	.012
Selection X Movement X Search	.829	.372	.035

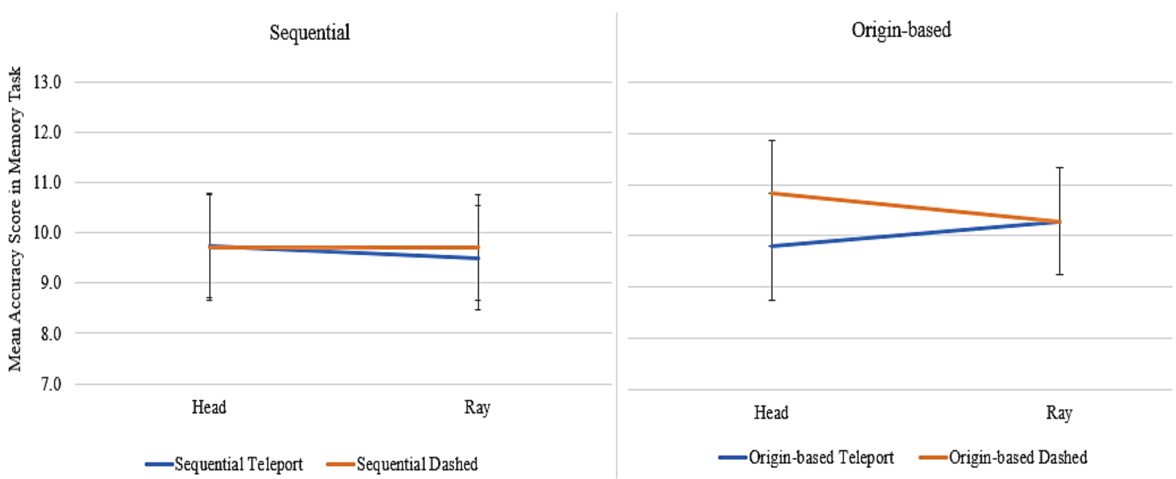

Figure 6: Mean ACC in memory task by selection and movement per search.

2.3.2 Physical Stress

Physical stress was tested and measured by examining a discomfort rating scale that incorporated disorientation, dizziness, and queasiness symptoms to examine any differential impact of interface design on participant physical stress. The analysis revealed two significant outliers that were due to a recording error; these were therefore excluded from the analysis. As shown in Table 11, the lowest rating of discomfort was found in condition 2, with the head-teleport-origin combination of interface factors.

Table 11: Mean discomfort rating per condition

	Discomfort Rating	
	M	*SD*
Condition 1 (head teleport sequential)	4.27	1.64
Condition 2 (head teleport origin)	**4.00**	**1.31**
Condition 3 (head dashed sequential)	4.68	1.64
Condition 4 (head dashed origin)	4.59	1.79
Condition 5 (ray teleport sequential)	4.73	1.93
Condition 6 (ray teleport origin)	4.36	1.76
Condition 7 (ray dashed sequential)	4.14	1.70
Condition 8 (ray dashed origin)	4.14	1.58

Note. The bolded text highlights the condition with the lowest discomfort rating.

As seen in Table 12, there were no significant main effects of selection or movement on the discomfort rating. There was a marginal effect of search, such that the lowest discomfort rating was found in the origin-based method. As seen in Figure 7, confidence intervals indicate that it was driven by the ray-teleport combination of interface designs. As illustrated in Figure 8, there was a significant two-way interaction between selection and movement such that the head selection was associated with a lower discomfort rating when combined with the teleport movement, but not the dashed (across both search methods). In contrast, the ray selection was associated with lower discomfort rating when combined with the dashed movement, but not the teleport (across both search methods). Confidence intervals confirmed the significant two-way interaction between selection and movement across all combinations of interface designs. All other interactions were non-significant.

Table 12: Tests of main effects and interactions on discomfort rating

Variable	$F(1, 21)$	p	η_p^2
Selection	.062	.805	.003
Movement	.157	.696	.007
Search	**3.118**	**.092**	**.129**
Selection X Movement	**4.875**	**.039**	**.188**
Selection X Search	0.000	1.000	.000
Movement X Search	0.615	.442	.028
Selection X Movement X Search	0.151	.702	.007

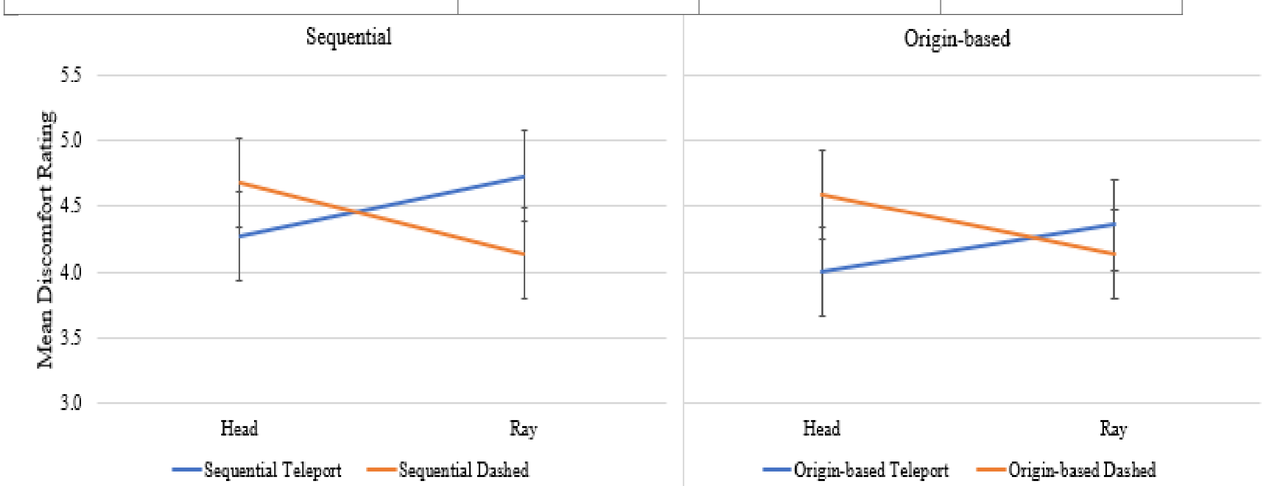

Figure 7: Mean discomfort rating by selection and movement per search.

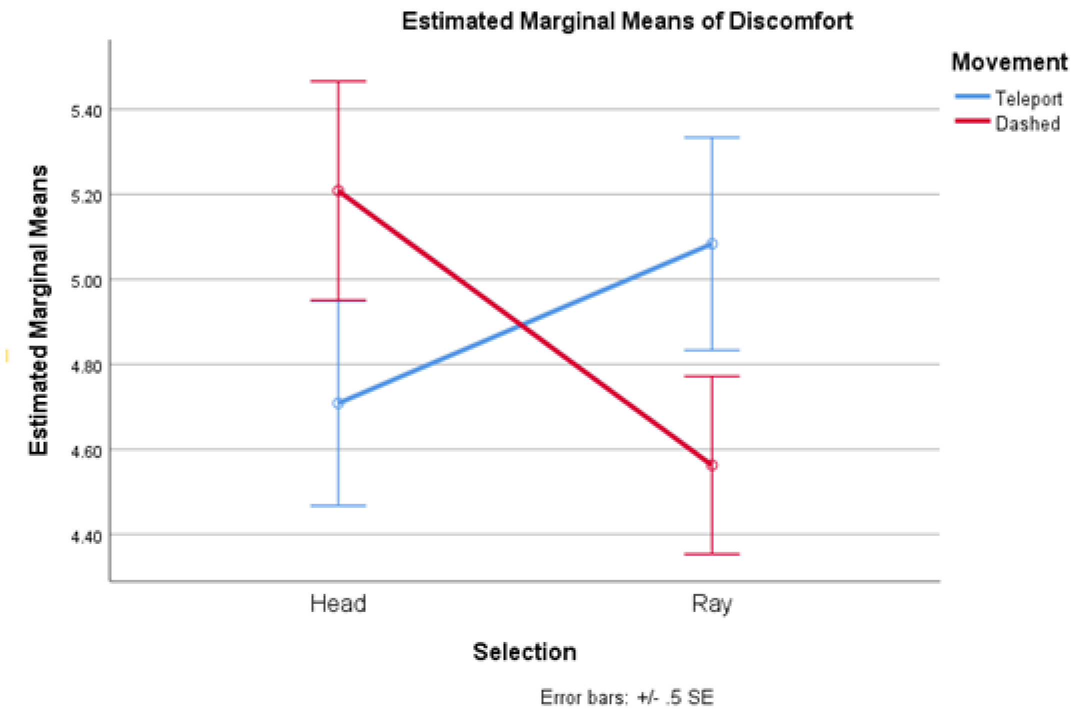

Figure 8: Mean discomfort rating by selection and movement across both search methods.

2.3.3 Qualitative Feedback

Participants were asked to reflect their preferred method of selection, movement, and search once the entire experiment was completed. See Figure 9 below for a summary of feature preference counts.

Q1: Do you believe you performed better using the head or ray to select entities? Please explain.

Head = 16, Ray = 6, No difference = 2

The majority (16/24) reported that they performed better on the task when using their head to select targets. Of these participants, the common explanation was that they found the head selection method easier to control as it allowed for simpler movements and more gaze time before selection. Six of the participants reported the ray selection improved their performance, giving the explanation that it has a more realistic feeling. Two of the participants did not report any noticeable difference between the selection methods. A one-sample binomial test revealed that the head selection was marginally significantly more likely to be perceived as associated with better performance than with the ray selection, $p = .052$.

Q2: Do you believe you performed better when dashed to entities or when teleported? Please explain.

Dashed = 12, Teleport = 7, No difference = 5

Half (12/24) reported that they performed better when dashed to entities. Of these participants, the common explanation was that they found it aided recall by allowing more gaze time while approaching the entity and the ability to approximate relative distances. Seven of the participants reported the teleport method was more comfortable and did not produce and interference from the other entities. Five of the participants did not report any noticeable difference between the search methods. A one-sample binomial test revealed that the dashed and teleport movement methods were equally likely to be perceived as associated with better performance, $p = .359$.

Q3: Do you believe you performed better when sequentially moving between entities or when placed back at an origin? Please explain.

Sequential = 7, Origin = 15, No difference = 2

The majority (15/24) reported that they performed better when in an origin-based search method. Of these participants, the common explanation was that they found it easier to determine the target locations when using both egocentric and allocentric strategies. Seven of the participants reported the sequential search method improved their performance as they were able to remember their path progression. Two of the participants did not report any noticeable difference between the search methods. A one-sample binomial test revealed that the origin-based and sequential search methods were equally likely to be to be perceived as associated with better performance, $p = .134$.

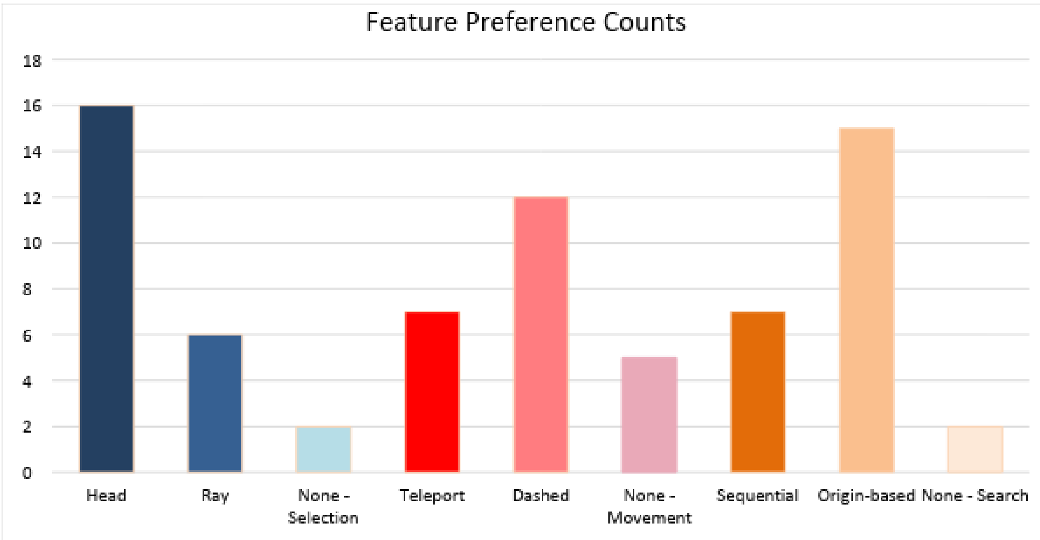

Figure 9: Feature preference counts on the qualitative feedback task

2.3.4 Correlation Analysis

A correlation analysis was performed to examine the relationship between different factors that are incorporated in Endsley's model of situation awareness. As shown in Table 13, SA Level 1 RT had a moderate positive correlation with SA Level 2 RT ($p = .029$) and SA Level 2 ACC ($p = .022$), indicating that the faster participants were in the interrogation task, the faster they were in the memory task, but they were less accurate. All other measures did not show any significant correlations.

Table 13: Spearman's rank order correlations among grand total measures

	1	2	3
1. SA Level 1 RT	-		
2. SA Level 2 RT	**.457***	-	
3. SA Level 2 ACC	**.465***	.125	-
4. Discomfort Rating	-.176	-.262	.088

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

2.4 Discussion

2.4.1 Interface Design on Situation Awareness and Physical Stress

Table 14: Summary of hypothesized best interface designs

Dependent Variable	**Hypothesized Best Interface**		
	Selection	**Movement**	**Search**
1.SA Level 1 RT - Interrogation Task	Head (Hypothesis 1A)	Dashed (Hypothesis 1B)	Origin-Based (Hypothesis 1C)
2.SA Level 2 RT - Memory Task	Head (Hypothesis 2A)	Dashed (Hypothesis 2B)	Origin-Based (Hypothesis 2C)
3.SA Level 2 ACC - Memory Task	Head (Hypothesis 3A)	Dashed (Hypothesis 3B)	Origin-Based **(Hypothesis 3C)**
4.Physical Stress - Discomfort Rating	Head (Hypothesis 4A)	Dashed (Hypothesis 4B)	Origin-Based **(Hypothesis 4C)**

SA Level 1 RT

As a main effect of selection was not seen in the response times in the interrogation task, hypothesis 1A was not confirmed. However, the head selection method was associated with the fastest responses in the interrogation task. A possible explanation is that the head selection modified the virtual environment less by not incorporating a ray from the hand. A review of object selection techniques done by Argelaguet and Andujar (2012) suggests that pointing techniques, as seen in the ray selection, could modify how the objects are viewed by introducing the possibility for object occlusion and altered depth perception (Argelaguet & Andujar, 2012). Qualitative feedback also confirmed that participants believed they performed better using the head selection over the ray selection.

As a main effect of movement was not seen in the response times in the interrogation task, hypothesis 1B was not confirmed. However, there was a marginal two-way interaction for selection by movement, such that the teleport movement was associated with faster response times when combined with head selection, and the dashed movement was associated with faster response times when combined with the ray selection. As a significant three-way interaction emerged between all three factors, the selection and movement interaction advantages were only seen in the sequential, not origin-based, search. As mentioned above, the head selection was associated with the fastest response, so it seems likely that teleporting to entities could lower response times on the interrogation task.

A marginal main effect of search was found in the response times in the interrogation task such that the sequential search method had faster response times; therefore, hypothesis 1C was rejected. Research by Wolbers and Hegarty (2010) suggests that navigating environments quickly and accurately requires a combination of self-movement (egocentric spatial processing) and the perception of spatial relationships of the environment (allocentric spatial processing). The present results seem to conflict the theory Wolbers and Hegarty proposed as sequential search only makes use of egocentric spatial processing. As explained above, significant interactions did emerge and therefore it seems as though more research should be conducted to examine which combination of interface designs will allow faster response times in the interrogation task.

SA Level 2 RT

As main effects of selection, movement, and search were not seen in the response times on the memory task, hypothesis 2A, 2B, and 2C were not confirmed. Further research should be done to confirm this result.

SA Level 2 ACC

As main effects of selection and movement were not seen in the accuracy scores in the memory task, hypothesis 3A and 3B were not confirmed. As a marginal main effect of search was found indicating that origin-based search had higher accuracy scores, hypothesis 3C was confirmed. Qualitative feedback indicated that more participants preferred an origin-based search, however this effect was not significant. The present results support the theory proposed by Wolber and Hegarty (2010) that taking advantage of both allocentric and egocentric spatial processing, as seen in origin-based search, helps in cognitive map formation. As these results conflict the marginal advantage of sequential search on SA Level 1 RT, further research to confirm the value of the origin-based search method is necessary, particularly as a tradeoff between search times and accuracy for the memory task was observed, as discussed further below.

Physical Stress

As a main effect of selection was not seen in discomfort ratings, hypothesis 4A was not confirmed. However, the head selection was found in the combination of interface designs that showed the lowest discomfort rating (i.e., head teleport origin). Qualitative feedback indicated that participants believed they performed better using the head selection over the ray selection. Research by Kim et al. (2007) suggests that the head selection arouses the user's interest and provides an enhanced sense of immersion to explain this preference.

As a main effect of movement was not seen in the discomfort ratings, hypothesis 4B was not confirmed. However, there was a significant interaction between selection and movement in which the teleport movement afforded less discomfort when combined with a head selection, but not the ray selection. As mentioned above, the head selection was found in the combination that afforded the lowest discomfort rating and so it seems likely that teleporting to entities could decrease discomfort. However, based on qualitative feedback, participants preferred a dashed movement as it allowed them more time to view entities during movement progression. It therefore seems necessary to further investigate which movement method decreases physical stress.

As a marginal main effect of search was found indicating that origin-based search had lower discomfort scores, hypothesis 4C was confirmed. It seems possible that an origin-based search lowered discomfort scores and was less physically stressful on the participants due to the familiarity of a central starting and ending point. This phenomenon has been described by Thompson and Spencer (1966) as habituation and refers to a simple, non-associative learning in which the magnitude of someone's response to a specific stimulus decreases with repeated exposure to it. With regards to the present results, it seems likely that participants became habituated to a view of the environment from the origin and were therefore less physically stressed by the task.

2.4.2 Correlation Analysis of Grand Total Measures

Summary of Hypotheses:

Table 15: Summary of hypothesized correlations of grand total measures

Dependent Variable	**Hypothesized Correlations**		
	1	**2**	**3**
1.SA Level 1 RT - Interrogation Task	--		
2.SA Level 2 RT - Memory Task	Positive **(Hypothesis 1D)**	--	
3.SA Level 2 ACC - Memory Task	Negative (Hypothesis 1E)	Negative (Hypothesis 2D)	--
4.Physical Stress - Discomfort Rating	Positive (Hypothesis 1F)	Positive (Hypothesis 2E)	Negative (Hypothesis 3D)

As a significant correlation emerged indicating that SA Level 1 RT was positively correlated with SA Level 2 RT, hypothesis 1D was confirmed. The correlation of response times in both tasks suggests that participants who were able to perceive the environment in the interrogation task quickly were also faster to remember it in the memory task. The correlation between the time it takes to perceive the environment and the time it takes to comprehend where objects are in relation to each other is supported by Endsley's 1995 model of situation awareness in which Level 2 is dependent on and builds upon information from Level 1.

With regards to hypothesis 1E, the correlation analysis revealed a significant correlation between SA Level 1 RT and SA Level 2 ACC, however it was positive. Therefore, hypothesis

1E was rejected. Participants that were quicker to perceive the environment in the interrogation task were less accurate in remembering it in the memory task, suggesting a possible tradeoff in which speed compromises memory recall. This speed-accuracy tradeoff theory (SAT) has been researched since as early as 1899 in a dissertation by Woodworth and refers to how the accuracy of a task is a function of how long it takes to complete. Therefore, participants who were in the interrogation task for a shorter duration had less time to consolidate the spatial relationships between the objects and therefore had lower accuracy when trying to remember them in the memory task.

As no other significant correlations emerged, hypotheses 1F, 2D, 2E, and 3D were not confirmed.

2.4.3 Continuing Remarks

A second experiment to clarify the understanding of how interface design factors influence situation awareness formation in airborne surveillance tasks was proposed. As the head selection was always associated with the best combination of interface designs on all measures of Experiment 1, and it was preferred by most participants, it was determined to eliminate the ray-based selection method from Experiment 2. Operator movement and search method showed conflicting results and were therefore included for further analysis in Experiment 2. Additionally, Experiment 2 was conducted to confirm the previous results regarding the correlation analysis. Lastly, it was proposed that measures of mental workload be included in Experiment 2 to examine the relationship between mental workload and situation awareness on airborne surveillance tasks. The addition of a mental workload variable was important as it provided another method for identifying which search or movement method was superior. As previously discussed, mental workload and situation awareness have been hypothesized to diverge due to the limited capacity of working memory and processing speed (Endsley, 1995). Due to the theory that increasing perceptual loads is correlated to decreases in working memory and impairment on tasks that measure situation awareness, it is of interest to examine if a correlation exists by examining the results of Experiment 2.

3 Chapter: EXPERIMENT 2

Similar to Experiment 1, Experiment 2 was designed to investigate if the different interface design factors could influence situation awareness and operator physical stress and if a relationship existed between the two. Experiment 2 replicated the same methods as Experiment 1, however removed the object selection factor as the benefits were clear for the head selection in Experiment 1. All results from Experiment 1 proved the head selection was always in the best combination of interface designs and was therefore deduced to be the more effective selection method.

Experiment 2 was also designed to investigate if a correlation existed between operator mental workload and situation awareness. This was done by examining performance on a peripheral detection task (PDT) where participants were asked to press a button in response to auditory tones. Additionally, mental workload was examined by measuring the number of peaks in electrodermal activity by monitoring data from an Empatica E4 wristband. These measures of mental workload were included to examine if they yielded any relationship to operator situation awareness and/or physical stress.

3.1 Method

3.1.1 Participants

Twenty-four (n = 24) Carleton University undergraduate students were recruited and tested using the university's online experiment sign-up system. Participants were compensated by receiving 2% credit in one of their university classes. Participation criteria included having normal or corrected-to-normal vision and no diagnosis of colour blindness. The sample included 11 females and 13 males and had an average age of 19 years old (*SD* = 1.82).

3.1.2 Equipment and Virtual Environment

The equipment and virtual environment were identical to Experiment 1; however, included two additional input devices: the Oculus remote, which allowed participants to make button presses in response to auditory tones, and an Empatica E4 wristband to allow recording of peaks in electrodermal activity. See Experiment 1 – Method – Equipment and Virtual Environment for a detailed description of the equipment and virtual environment used.

3.1.3 Design

A 2 (Movement: teleport, dashed) by 2 (Search: sequential, origin-based) repeated measures design was conducted. As seen in Table 16, the two interface factors were crossed to create four unique conditions. Each condition was blocked and counterbalanced following a Latin-Squares design. See Experiment 1 – Method – Design for a detailed description of the interface factors.

Table 16: Corresponding interface factors for each condition

	Interface Factor	
	Movement	*Search Method*
Condition 1	Teleport	Sequential
Condition 2	Teleport	Origin-based
Condition 3	Dashed	Sequential
Condition 4	Dashed	Origin-based

3.1.4 Tasks

The tasks were identical to Experiment 1; however, there was one additional task incorporated in Experiment 2. See Experiment 1 – Method – Tasks for a detailed description of the interrogation and memory task.

Peripheral Detection Task: The third task was an ongoing peripheral detection task in which participants had to respond to an auditory stimulus throughout both the interrogation and memory tasks. Any time the participants heard a tone they were asked to respond with a button press. The purpose of this task was to measure the mental workload associated within each condition. A peripheral detection task is sensitive to mental workload such that the hit rate to the tones lowers and the response time increases when mental workload increases (Martens & Winsum, 2000).

3.1.5 Procedure

The procedure was identical to Experiment 1; however, participants were also asked to wear an Empatica E4 wristband to measure their peaks in electrodermal activity. High amounts of mental workload have been suggested to correspond to increased EDA as measured using non-invasive psychophysiological sensors (Lo, Sehic, & Meijer, 2017). See Experiment 1 – Method – Procedure for a detailed description.

3.1.6 Dependent Variables

There were four dependent variables measured: SA Level 1, SA Level 2, Physical Stress, and Mental Workload. As seen in Table 17, the associated measures are listed for each dependent variable. See Experiment 1 – Method – Dependent Variables for a detailed description of the measures associated with SA Level 1, SA Level 2, and Physical Stress.

Table 17: Dependent variables and associated measures

Dependent Variable	Measure
SA Level 1	Response Time on Interrogation Task (SA Level 1 RT)
SA Level 2	Response Time on Memory Task (SA Level 2 RT)
	Accuracy on Memory Task (SA Level 2 ACC)
Physical Stress	Scores on three Likert scales (Discomfort Rating [dizziness, queasiness, and disorientation])
Mental Workload	Hit Rate on Peripheral Detection Task (PDT HR)
	Response Time on Peripheral Detection Task (PDT RT)
	Peaks in Electrodermal Activity (EDA Peaks)

Mental Workload: This dependent variable was measured in three different ways: hit rate and response time on the PDT task, and by recording the number of peaks in electrodermal activity per condition. The hit rate on the PDT task was measured by taking the ratio of hits participants were recorded to misses in response to the auditory tones. Response time on the PDT task was measured by recording the average length of time it took participants to respond to the auditory tones. Peaks in electrodermal activity were measured from data recorded by the Empatica E4 wristband that participants were asked to wear. As there is a known drift associated with skin conductance, the phasic responses gave a stronger indication of mental workload within the conditions, as compared to the tonic response, as it is able to measure changes in arousal within small intervals of time (Braithwaite, Watson, Jones, & Rowe, 2015). EDA peaks were counted as any data point where the amplitude was 10% above a local 15 second local median.

3.2 Hypotheses

Endsley's model provided a platform for investigating the impact of virtual reality interface design on situation awareness and how it can influence the physical stress and mental workload of the operator. It is also an opportunity to examine if correlations exist between the different measures of situation awareness (SA Level 1 RT, SA Level 2 RT, SA Level 2 ACC), and if measures of physical stress (Discomfort Rating) and mental workload (PDT-HR, PDT-RT, and EDA Peaks) yield any relationship to each other or measures of situation awareness.

Interface Design on Situation Awareness, Physical Stress, and Mental Workload

Table 18: Summary of hypothesized best interface designs

Dependent Variable	Hypothesized Best Interface	
	Movement	**Search**
1.SA Level 1 RT - Interrogation Task	Dashed (Hypothesis 1A)	Origin-Based (Hypothesis 1B)
2.SA Level 2 RT - Memory Task	Dashed (Hypothesis 2A)	Origin-Based (Hypothesis 2B)
3.SA Level 2 ACC - Memory Task	Dashed (Hypothesis 3A)	Origin-Based (Hypothesis 3B)
4.Physical Stress - Discomfort Rating	Dashed (Hypothesis 4A)	Origin-Based (Hypothesis 4B)
5.Mental Workload - PDT HR	Dashed (Hypothesis 5A)	Origin-Based (Hypothesis 5B)
6.Mental Workload - PDT RT	Dashed (Hypothesis 6A)	Origin-Based (Hypothesis 6B)
7.Mental Workload - EDA Peaks	Dashed (Hypothesis 7A)	Origin-Based (Hypothesis 6B)

Hypothesis 1A, 2A, 3A, 4A: Dashed movement, as compared to teleport movement, will result in better SA Level 1 and SA Level 2 due to the integration of optic flow information. Dashed movement will also result in lower physical stress and mental workload due to the disorientation associated with an instantaneous movement.

Hypothesis 1B, 2B, 3B, 4B: Origin-based search, as compared to sequential search, will result in better SA Level 1 and SA Level 2 due to the ability to combine both allocentric and egocentric spatial processing strategies. Origin-based search will also result in lower physical stress and mental workload due to a constant cognitive map of the environment that lowers disorientation.

Correlation Analysis of Grand Total Measures

Table 19: Summary of hypothesized correlations of grand total measures

Dependent Variable	**Hypothesized Correlations**					
	1	**2**	**3**	**4**	**5**	**6**
1.SA Level 1 RT - Interrogation Task	--					
2.SA Level 2 RT - Memory Task	Positive (Hypothesis 1C)	--				
3.SA Level 2 ACC - Memory Task	Negative (Hypothesis 1D)	Negative (Hypothesis 2C)	--			
4.Physical Stress - Discomfort Rating	Positive (Hypothesis 1E)	Positive (Hypothesis 2D)	Negative (Hypothesis 3C)	--		
5.Mental Workload - PDT HR	Negative (Hypothesis 1F)	Negative (Hypothesis 2E)	Positive (Hypothesis 3D)	Negative (Hypothesis 4C)	--	

6.Mental Workload - PDT RT	Positive (Hypothesis 1G)	Positive (Hypothesis 2F)	Negative (Hypothesis 3E)	Positive (Hypothesis 4D)	Negative (Hypothesis 5C)	--
7.Mental Workload - EDA Peaks	Positive (Hypothesis 1H)	Positive (Hypothesis 2G)	Negative (Hypothesis 3F)	Positive (Hypothesis 4E)	Negative (Hypothesis 5D)	Positive (Hypothesis 6C)

Hypothesis 1C, 1E, 1G, 1H: SA Level 1 will be positively correlated with SA Level 2 RT, Physical Stress, PDT RT, and EDA Peaks. Participants who perceive the environment quickly will be faster to remember it and respond to a peripheral detection task. Participants who perceive the environment quickly will also be less discomforted and show less peaks in electrodermal activity.

Hypothesis 1D, 1H: SA Level 1 will be negatively correlated with SA Level 2 ACC and PDT HR. Participants who perceive the environment quickly will be more accurate in remembering it and will respond to the peripheral detection task more often.

Hypothesis 2C, 2E: SA Level 2 RT will be negatively correlated with SA Level 2 ACC and PDT HR. Participants who remember the environment quickly will be more accurate in remembering it and will respond to the peripheral detection task more often.

Hypothesis 2D, 2F, 2G: SA Level 2 RT will be positively correlated with Physical Stress, PDT RT, and EDA Peaks. Participants who remember the environment quickly will be less discomforted, will respond to the peripheral detection task quicker, and will show less peaks in electrodermal activity.

Hypothesis 3C, 3E, 3F: SA Level 2 ACC will be negatively correlated with Physical Stress, PDT RT, and EDA Peaks. Participants who are more accurate remembering the environment will be less discomforted, will respond to the peripheral detection task quicker, and will show less peaks in electrodermal activity.

Hypothesis 3D: SA Level 2 ACC will be positively correlated with PDT HR. Participants who are more accurate remembering the environment will respond to the peripheral detection task more often.

Hypothesis 4C: Physical Stress will be negatively correlated with PDT HR. Participants who are less discomforted will respond to the peripheral detection task more often.

Hypothesis 4D, 4E: Physical Stress will be positively correlated with PDT RT and EDA Peaks. Participants who are less discomforted will respond to the peripheral detection task quicker and will show less peaks in electrodermal activity.

Hypothesis 5C, 5D: PDT HR will be negatively correlated to PDT RT and EDA Peaks. Participants who respond to the peripheral detection task more often will be quicker to respond to it and show less peaks in electrodermal activity.

Hypothesis 6C: PDT RT will be positively correlated with EDA Peaks. Participants who respond faster to the peripheral detection task will show less peaks in electrodermal activity.

3.3 Results

A 2 (Movement: teleport, dashed) by 2 (Search: sequential, origin-based) ANOVA with both factors as repeated measures was conducted for each of the task measures. Separate tests were also conducted with counterbalance as a between-subject factor to test for order effects, with no significant overall main effects of counterbalance detected for any of the measures in Experiment 2. If not discussed, the data should be considered to have a normal distribution and be free from outliers. Outliers were tested for effects on the analysis (by comparing test results with and without the outliers) and were not removed if the effects were not altered by the outlier values. Tests of sphericity were conducted for the counterbalance tests, and Greenhouse-Geisser values were considered when the assumptions were not met. Because a repeated measures design was used, all marginal main and interaction effects, as per the F-statistic ($p < .1$ and $p > .05$), were examined using the confidence interval tests as recommended by Holland and Jarmasz (2009). As recommended by Cohen, the size of the effect was also evaluated using partial eta squared values, where 0.01 was small, 0.09 was medium, and 0.25 was considered large (Cohen, 1988). Finally, to elicit any possible pattern of interface effects the fastest response times (RT), highest accuracy (ACC), lowest physical discomfort, and best mental workload results are highlighted for each analysis.

3.3.1 SA Level 1

Perception of the environment (SA Level 1) was indexed by examining the RT on the entity interrogation task. As shown in Table 20, the fastest RT was found in condition 1, with the teleport-sequential combination of interface factors.

Table 20: Mean RT in interrogation task per condition

	RT	
	M	*SD*
Condition 1 (teleport sequential)	**97.14**	**35.81**
Condition 2 (teleport origin)	98.74	29.09
Condition 3 (dashed sequential)	98.42	32.80
Condition 4 (dashed origin)	106.21	42.54

Note. The bolded text highlights the condition with the fastest RT during the interrogation task.

As seen in Table 21, there was no significant main effect of movement or search on RT in the interrogation task. The interaction was also non-significant.

Table 21: Tests of main effects and interaction on SA Level 1 RT

Variable	$F(1, 23)$	p	η_p^2
Movement	.608	.443	.026
Search	2.010	.170	.080
Movement X Search	.912	.349	.038

3.3.2 SA Level 2

Comprehension of the environment (SA Level 2) was indexed by examining the RT and ACC for the entity memory task.

3.3.2.1 SA Level 2 Response Time

As shown in Table 22, the fastest RT was found in condition 2, with the teleport-origin combination of interface factors.

Table 22: Mean RT in memory task per condition

	RT	
	M	*SD*
Condition 1 (teleport sequential)	61.99	6.10
Condition 2 (teleport origin)	**59.21**	**4.62**
Condition 3 (dashed sequential)	66.17	5.31
Condition 4 (dashed origin)	59.26	4.72

Note. The bolded text highlights the condition with the fastest RT during the memory task.

As seen in Table 23, there was no significant main effect of movement on RT in the memory task. There was a significant main effect of search on RT in the memory task, such that the fastest RT was associated with the origin-based search method. As illustrated in Figure 10, confidence intervals indicate this effect of search was driven by the dashed movement. The interaction of search and movement was non-significant, such that the faster RT in the origin-based method held, regardless of movement type.

Table 23: Tests of main effects and interaction on SA Level 2 RT

Variable	$F(1, 23)$	p	η_p^2
Movement	.410	.528	.018
Search	**5.930**	**.023**	**.205**
Movement X Search	.529	.474	.022

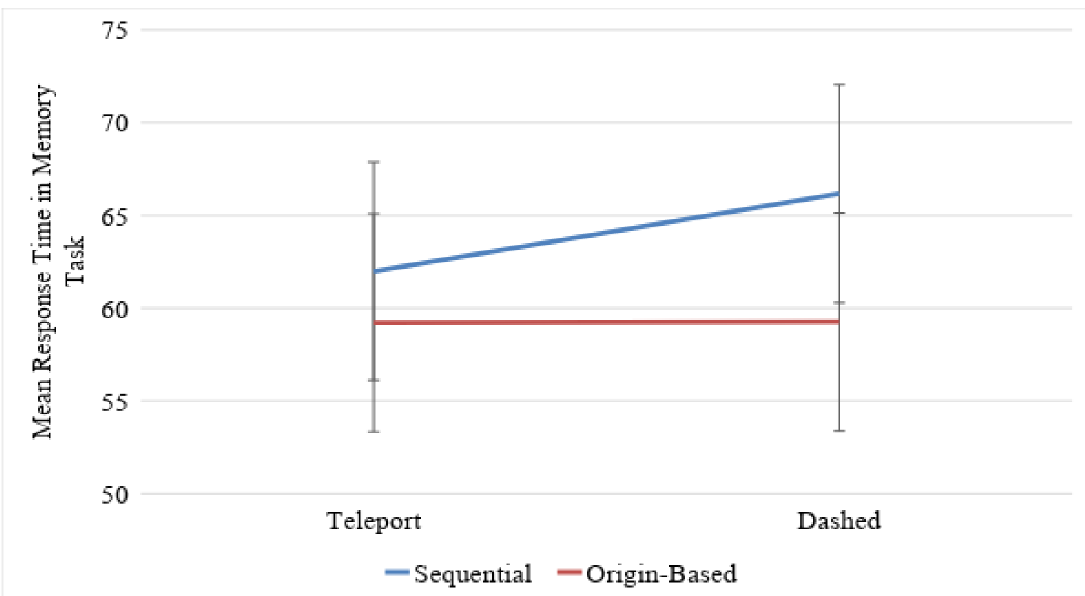

Figure 10: Mean RT in memory task by search and movement.

3.3.2.2 SA Level 2 Accuracy Score

As shown in Table 24, the highest ACC was found in condition 4, with the dashed-origin combination of interface factors.

Table 24: Mean ACC in memory task per condition

	ACC	
	M	*SD*
Condition 1 (teleport sequential)	16.41	5.87
Condition 2 (teleport origin)	18.12	4.10
Condition 3 (dashed sequential)	17.37	6.08
Condition 4 (dashed origin)	**19.95**	**5.18**

Note. The bolded text highlights the condition with the highest ACC during the memory task.

As seen in Table 25, there was no significant main effect of movement on ACC. A significant effect of search was found, such that the highest ACC was associated with the conditions which included the origin-based search method. As seen in Figure 11, confidence intervals indicate the significant effect of search was driven by both movement interfaces. The interaction was non-significant, indicating that higher ACC was found in the origin-based condition, regardless of movement type.

Table 25: Tests of main effects and interaction on SA Level 2 ACC

Variable	$F(1, 23)$	p	η_p^2
Movement	1.815	.191	.073
Search	**6.711**	**.016**	**.226**
Movement X Search	.378	.545	.016

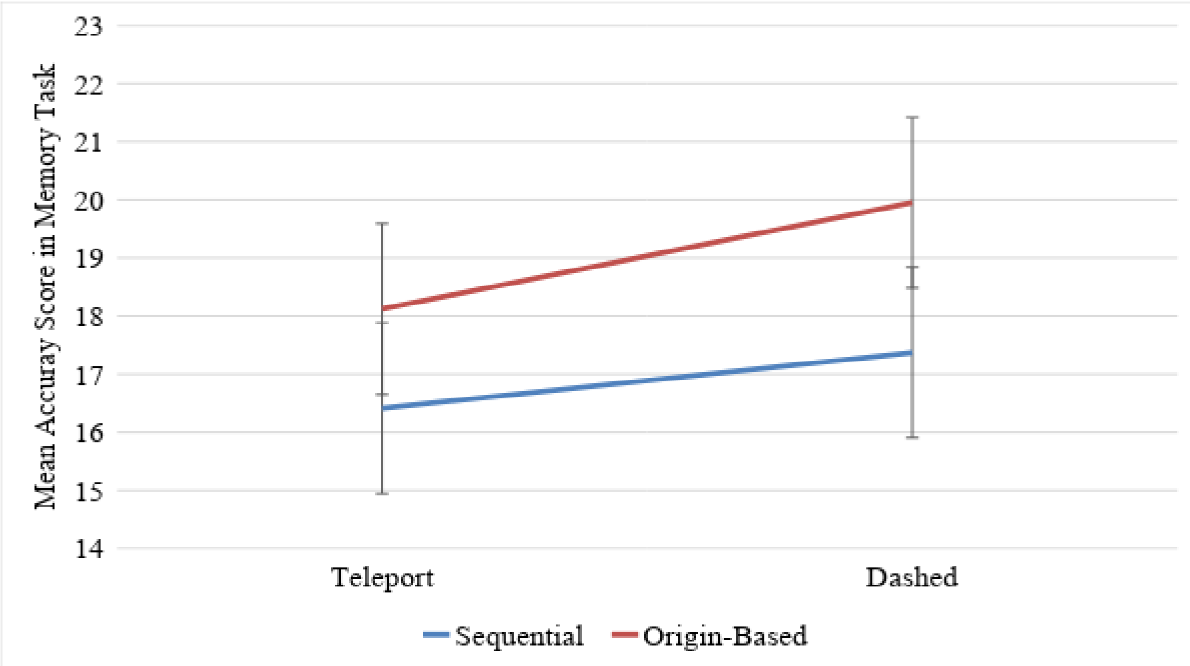

Figure 11: Mean ACC in memory task by search and movement.

3.3.3 Physical Stress

Physical stress was indexed by the discomfort rating scale that incorporated disorientation, dizziness, and queasiness symptoms. This analysis investigated any differential impact of interface design on participant physical stress. As shown in Table 26, the lowest rating of discomfort was found in condition 2, with the teleport-origin combination of interface factors.

Table 26: Mean discomfort rating per condition

	Discomfort Rating	
	M	*SD*
Condition 1 (teleport sequential)	4.35	1.80
Condition 2 (teleport origin)	**3.56**	**1.59**
Condition 3 (dashed sequential)	4.23	1.46
Condition 4 (dashed origin)	4.71	2.19

Note. The bolded text highlights the condition with the lowest discomfort rating.

As seen in Table 27, there was a significant main effect of movement on the discomfort rating such that the lowest discomfort was associated with the teleport movement. There was no significant main effect of search on the discomfort rating. As illustrated in Figure 12, the interaction between movement and search was significant, such that the teleport movement was significantly associated with a lower discomfort rating when combined with the origin-based search, but not the sequential. In contrast, the dashed movement was only somewhat less discomforting when combined with the sequential, when compared to the origin-based search. Confidence intervals indicated the significant main effect of movement and the two-way interaction were driven by both the dashed and teleport movement.

Table 27: Tests of main effects and interaction on discomfort rating

Variable	$\boldsymbol{F(1, 23)}$	$\boldsymbol{p}$	$\boldsymbol{\eta_p^2}$
Movement	**10.606**	**.003**	**.316**
Search	1.351	.257	.055
Movement X Search	**11.655**	**.002**	**.336**

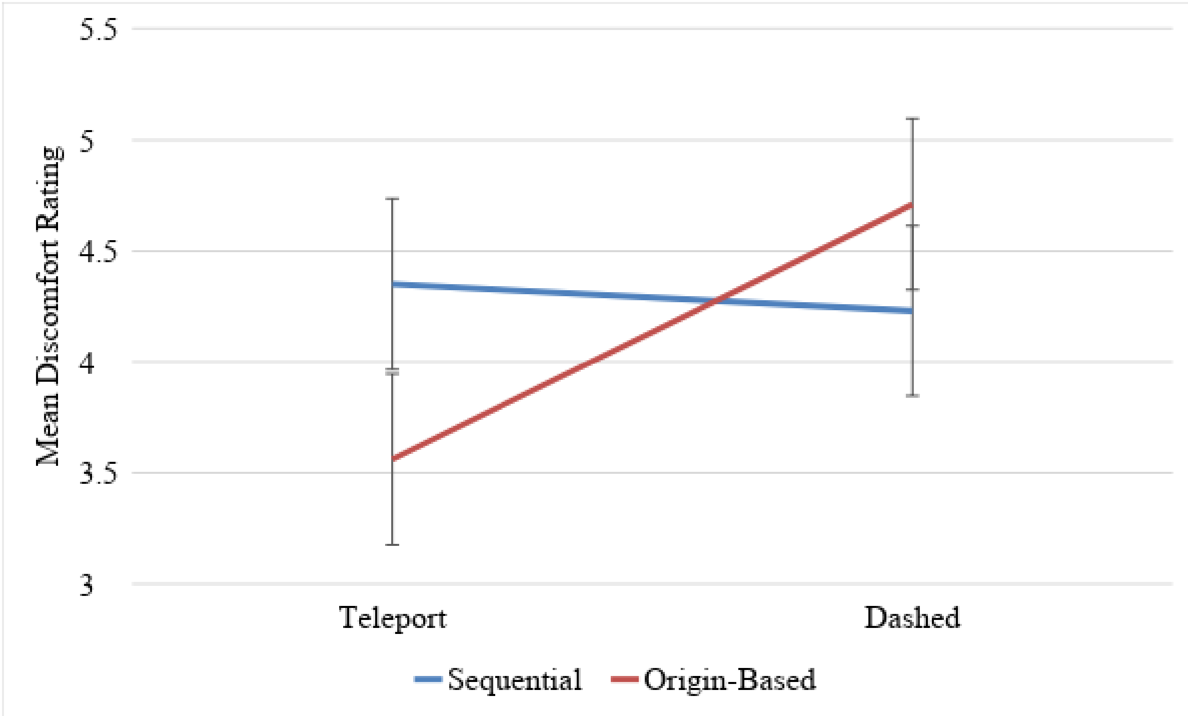

Figure 12: Mean discomfort rating by search and movement.

3.3.4 Mental Workload

Mental workload was indexed via a peripheral detection task in which participants had to make a button press in response to an auditory tone and their hit rate (HR) and RT were measured. Mental workload was also measured by counting the number of peaks in electrodermal activity (EDA peaks) that were recorded through the Empatica E4 wristband.

3.3.4.1 PDT - Hit Rate

Tests for normality indicated that the data was not normally distributed; therefore, the data was power transformed before running the analysis. As shown in Table 28, the highest HR was found in condition 1, although minimally, with the teleport-sequential combination of interface factors.

Table 28: Mean HR in the peripheral detection task per condition

	HR	
	M	*SD*
Condition 1 (teleport sequential)	**85.90**	**15.16**
Condition 2 (teleport origin)	85.29	16.66
Condition 3 (dashed sequential)	85.71	16.76
Condition 4 (dashed origin)	85.27	15.36

Note. The bolded text highlights the condition with the highest HR on the peripheral detection task.

As seen in Table 29, there was no significant main effect of movement or search on the HR to the tones. The interaction was also non-significant.

Table 29: Tests of main effects and interaction on HR

Variable	$F(1, 23)$	p	η_p^2
Movement	.379	.544	.016
Search	.136	.715	.006
Movement X Search	.045	.833	.002

3.3.4.2 PDT - Response Time

Tests for normality indicated that the data was not normally distributed; therefore, the data was log transformed. As shown in Table 30, the fastest RT was found in condition 2, although minimally, with the teleport-origin combination of interface factors.

Table 30: Mean RT in the peripheral detection task per condition

	RT	
	M	*SD*
Condition 1 (teleport sequential)	1.08	.308
Condition 2 (teleport origin)	**1.03**	**.362**
Condition 3 (dashed sequential)	1.07	.351
Condition 4 (dashed origin)	1.07	.358

Note. The bolded text highlights the condition with the lowest RT on the peripheral detection task.

As seen in Table 31, there was no significant main effect of movement or search on the RT. The interaction was also non-significant.

Table 31: Tests of main effects and interaction on RT in the peripheral detection task

Variable	$F(1, 23)$	p	η_p^2
Movement	.345	.563	.015
Search	1.858	.186	.075
Movement X Search	1.353	.257	.056

3.3.4.3 EDA Peaks

Tests for normality indicated that the data was not normally distributed; therefore, the data was square root transformed before running the analysis. As shown in Table 32, the least number of EDA peaks were found in condition 4, with the dashed-origin combination of interface factors.

Table 32: Mean EDA peaks per condition

	EDA Peaks	
	M	*SD*
Condition 1 (teleport sequential)	78.04	68.68
Condition 2 (teleport origin)	62.92	58.41
Condition 3 (dashed sequential)	73.71	84.85
Condition 4 (dashed origin)	**59.88**	**62.52**

Note. The bolded text highlights the condition with the lowest EDA peaks.

As seen in Table 33, there was no significant main effect of movement or search on the EDA peaks. The interaction was also non-significant.

Table 33: Tests of main effects and interaction on EDA peaks

Variable	$F(1, 23)$	p	η_p^2
Movement	.812	.377	.034
Search	1.426	.245	.058
Movement X Search	.128	.724	.006

3.3.5 Qualitative Feedback

Participants were asked to reflect their preferred method of movement and search once the entire experiment was completed. One participant response was lost due to a recording error. See Figure 13 below for a summary of feature preference counts.

Q1: Do you believe you performed better when dashed to entities or when teleported? Please explain.

Dashed = 9, Teleport = 8, No difference = 6

Nine participants reported that they performed better when dashed to entities. Of these participants, the common explanation was that they found it aided recall by allowing more gaze time while approaching the entity and the ability to approximate relative distances. Eight of the participants reported the teleport method was more comfortable and did not produce any interference from the other entities. Six of the participants did not report any noticeable difference between the search methods. A one-sample binomial test revealed that the dashed and teleport movement methods were equally likely to be perceived as associated with better performance, $p = 1.00$.

Q2: Do you believe you performed better when sequentially moving between entities or when placed back at an origin? Please explain.

Sequential = 4, Origin = 18, No difference = 1

The majority (18/24) reported that they performed better when in an origin-based search method. Of these participants, the common explanation was that they found it easier to determine the target locations when using an allocentric strategy. Four of the participants reported the sequential search method improved their performance as they were able to remember their path progression. One participant did not report any noticeable difference between the search methods. A one-sample binomial test revealed that the origin-based search method was significantly more likely to be perceived as associated with better performance, $p = .004$.

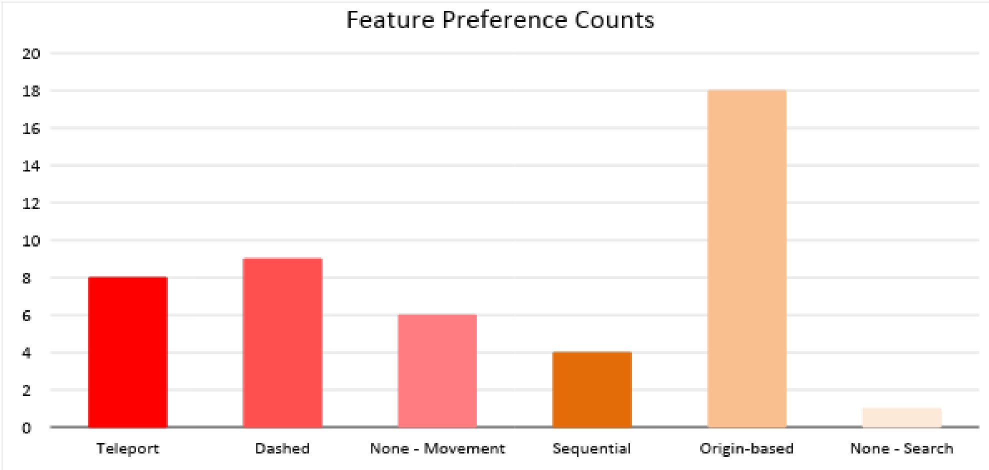

Figure 13: Feature preference counts on the qualitative feedback task

3.3.6 Correlation Analysis

A correlation analysis was performed to examine the relationship between different factors that are incorporated in Endsley's model of situation awareness. As shown in Table 34, SA Level 1 RT had a moderate positive correlation with SA Level 2 RT (p = .001), indicating that the quicker participants were in the interrogation task, the faster they were in the memory task. Additionally, the discomfort rating participants gave had a moderate negative correlation with their SA Level 2 ACC (p = .020), indicating participants were more accurate when they reported less discomfort. Lastly, it was found that the PDT HR had a moderate negative correlation to the PDT RT (p = .004), indicating that the faster participants were to respond, the more tones they responded to on average. No other significant correlations were found between the study measures.

Table 34: Spearman's rank order correlations among grand total measures

	1	2	3	4	5	6
1. SA Level 1 RT	-					
2. SA Level 2 RT	**.617****	-				
3. SA Level 2 ACC	.343	.226	-			
4. Discomfort Rating	-.308	-.003	**-.472***	-		
5. PDT HR	-.173	.122	.309	-.193	-	
6. PDT RT	.063	.222	.009	.287	**-.561****	-
7. EDA Peaks	-.150	.084	.127	-.352	-.040	-.014

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

3.4 Discussion

3.4.1 Interface Design on Situation Awareness, Physical Stress, and Mental Workload

Table 35: Summary of hypothesized best interface designs

Dependent Variable	**Hypothesized Best Interface**	
	Movement	**Search**
1.SA Level 1 RT - Interrogation Task	Dashed (Hypothesis 1A)	Origin-Based (Hypothesis 1B)
2.SA Level 2 RT - Memory Task	Dashed (Hypothesis 2A)	Origin-Based **(Hypothesis 2B)**
3.SA Level 2 ACC - Memory Task	Dashed (Hypothesis 3A)	Origin-Based **(Hypothesis 3B)**
4.Physical Stress - Discomfort Rating	Dashed (Hypothesis 4A)	Origin-Based (Hypothesis 4B)
5.Mental Workload - PDT HR	Dashed (Hypothesis 5A)	Origin-Based (Hypothesis

		5B)
6.Mental Workload - PDT RT	Dashed (Hypothesis 6A)	Origin-Based (Hypothesis 6B)
7.Mental Workload - EDA Peaks	Dashed (Hypothesis 7A)	Origin-Based (Hypothesis 6B)

SA Level 1 RT

As main effects of movement and search were not seen in the response times in the interrogation task, hypotheses 1A and 1B were not confirmed.

SA Level 2 RT

As a main effect of movement was not seen in the response times in the memory task, hypothesis 2A was not confirmed. Hypothesis 2B was confirmed as a significant main effect of search was found, such that the fastest response times in the memory task were associated with the origin-based search method. Research by Wolbers and Hegarty (2010) suggests that navigating environments quickly and accurately requires a combination of self-movement (egocentric spatial processing) and the perception of spatial relationships of the environment (allocentric spatial processing). The present results support the theory proposed by Wolber and Hegarty (2010) that taking advantage of both allocentric and egocentric spatial processing, as seen in origin-based search, helps in cognitive map formation and would decrease response times when attempting to remember information about the environment and the spatial relationships within it.

SA Level 2 ACC

As a main effect of movement was not seen in the accuracy scores in the memory task, hypothesis 3A was not confirmed. Hypothesis 3B was confirmed as a significant main effect of search was found, such that the highest accuracy scores in the memory task were associated with the origin-based search method. The present results continue to support the theory proposed by Wolber and Hegarty (2010) that taking advantage of both allocentric and egocentric spatial processing helps in cognitive map formation and would improve the memory recall of spatial relationships.

Physical Stress

As a significant main effect of movement was found, such that the teleport movement had lower discomfort ratings, hypothesis 4A was rejected. It had been assumed that dashed movement would decrease disorientation and therefore result in lower physical stress; instead it seems likely that the optic flow associated with the dashed movement caused the onset of cybersickness in the operator, as seen in research done by Davis et al. (2015). Hypothesis 4B was not confirmed as a main effect of search was not seen in the discomfort ratings. However, the two-way interaction between both factors was significant, such that the teleport movement was associated with a lower discomfort rating when combined with the origin-based search, and the dashed movement was associated with a lower discomfort rating when combined with the sequential search. It therefore seems likely that an origin-based search method could lower discomfort but only when combined with a teleport movement. Additionally, qualitative feedback from participants indicated a strong preference for the origin-based search method due to a constant cognitive map of the environment.

Mental Workload - PDT HR

As main effects of movement and search were not seen in the hit rate of the peripheral detection task, hypotheses 5A and 5B were not confirmed.

Mental Workload - PDT RT

As main effects of movement and search were not seen in the response times of the peripheral detection task, hypothesis 6A and 6B were not confirmed.

Mental Workload - EDA Peaks

As main effects of movement and search were not seen in the number of EDA peaks, hypothesis 7A and 7B were not confirmed.

3.4.2 Correlation Analysis of Grand Total Measures

Table 36: Summary of hypothesized correlations of grand total measures

Dependent Variable	**Hypothesized Correlations**					
	1	**2**	**3**	**4**	**5**	**6**
1.SA Level 1 RT - Interrogation Task	--					
2.SA Level 2 RT - Memory Task	Positive **(Hypothesis 1C)**	--				
3.SA Level 2 ACC - Memory Task	Negative (Hypothesis 1D)	Negative (Hypothesis 2C)	--			
4.Physical Stress - Discomfort Rating	Positive (Hypothesis 1E)	Positive (Hypothesis 2D)	Negative **(Hypothesis 3C)**	--		
5.Mental Workload - PDT HR	Negative (Hypothesis 1F)	Negative (Hypothesis 2E)	Positive (Hypothesis 3D)	Negative (Hypothesis 4C)	--	
6.Mental Workload - PDT RT	Positive (Hypothesis 1G)	Positive (Hypothesis 2F)	Negative (Hypothesis 3E)	Positive (Hypothesis 4D)	Negative **(Hypothesis 5C)**	--
7.Mental Workload - EDA Peaks	Positive (Hypothesis 1H)	Positive (Hypothesis 2G)	Negative (Hypothesis 3F)	Positive (Hypothesis 4E)	Negative (Hypothesis 5D)	Positive (Hypothesis 6C)

When examining the results from the correlation analysis, Hypothesis 1C that SA Level 1 RT would be positively correlated with SA Level 2 RT was confirmed. The correlation of response times in both task tasks suggests that participants who were able to perceive the environment in the interrogation task quickly were also faster to remember it in the memory task. The correlation between the time it takes to perceive the environment and the time it takes to comprehend where objects are in relation to each other is supported by Endsley's 1995 model of situation awareness in which Level 2 is dependent on and builds upon information from Level 1.

Hypothesis 3C that SA Level 2 ACC would be negatively correlated with Physical Stress was confirmed. The correlation of accuracy scores in the memory task and discomfort rating scores suggests that participants who were better at remembering the environment were also less discomforted.

Hypothesis 5C that PDT HR would be negatively correlated to PDT RT was confirmed. The correlation of hit rate and response time to the tones in the PDT task suggests that participants who detected the tones more often were also quicker to respond to them.

As no other significant correlations emerged, hypotheses 1D-H, 2C-G, 3E-F, 4C-E, 5D, and 6C were not confirmed. This lack of a significant correlation between physical stress and mental workload suggests that the tasks chosen in the experiment did not elicit changes in mental workload large enough to be captured via these indices of mental workload (e.g., HR and RT on the PDT task and EDA Peaks).

4 Chapter: GENERAL DISCUSSION

4.1 Summary of Findings

The objectives of the present research were to (a) determine if interface design factors within a virtual environment directly affect situation awareness, (b) determine if interface design factors within a virtual environment directly affect physical stress and operator mental workload, and (c) determine the relation of physical stress and mental workload to situation awareness. The present research was done to gain insight on how virtual reality interfaces should be designed to improve airborne surveillance tasks by increasing the situation awareness and lowering the physical stress of the operator. It was also conducted to examine if a relationship exists between a flight operator's situation awareness, mental workload, and physical stress, as indicated by Endsley's model of situation awareness. Two experiments were conducted and reported.

A comprehensive model of the results from both experiments is presented in Figure 14. Experiment 1 is presented with black lines and Experiment 2 with blue lines. Significant effects, where the interface factor strongly improved performance, are depicted as solid arrows and marginal effects, where the interface factor moderately improved performance, are depicted as dashed arrows. The model also presents any correlations seen between the measures as double dashed lines where (+) indicates a positive correlation and a (-) indicates a negative correlation.

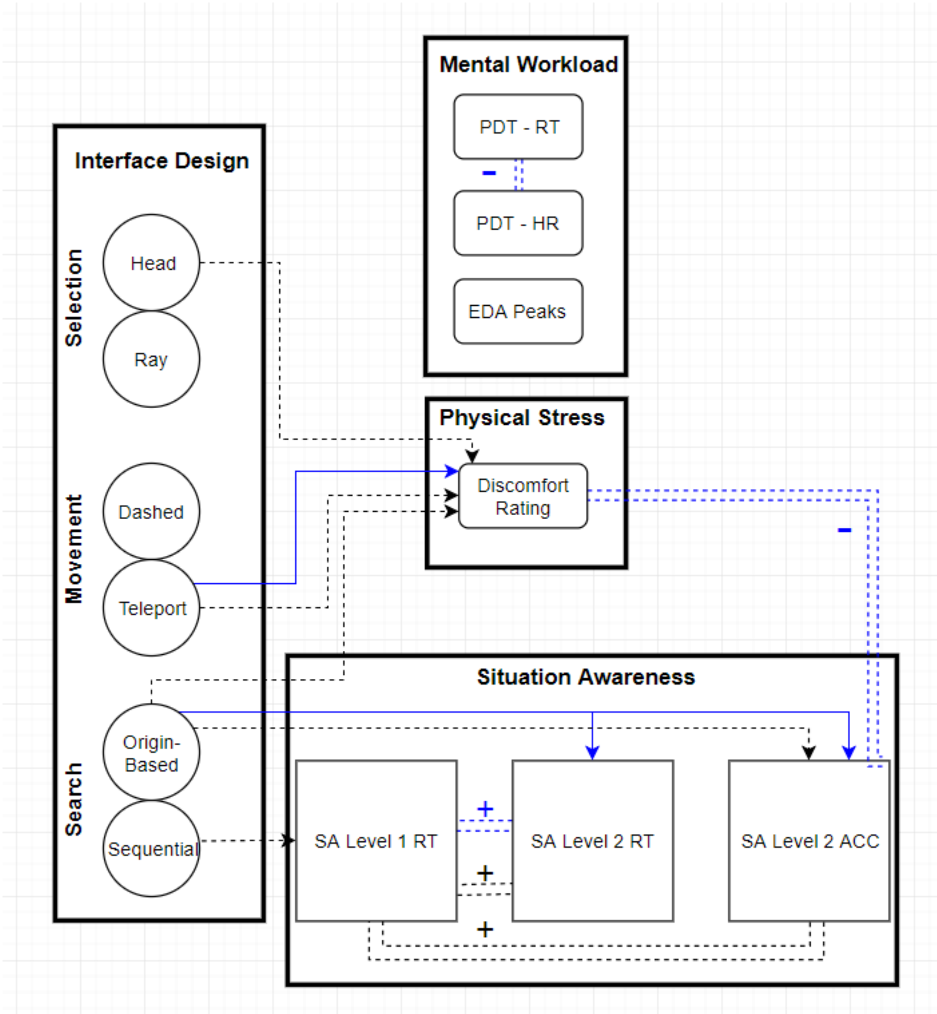

Figure 14: Comprehensive model of the obtained results found in Experiment 1 and 2

To address the first objective to determine if interface design factors within a virtual environment directly affect situation awareness, it can be seen across both experiments that the search method was the only factor of significance. As seen in the model, a sequential search improved the perception of the environment (SA Level 1) moderately; however, an origin-based search improved the comprehension of the environment (SA Level 2) strongly. By investigating the literature, it seems likely that allocentric strategies, seen only in the origin-based search, hinder the initial perception of the environment, but that over time they increase comprehension and memory recall, as found in fMRI research done by Jordan et al. (2004). Both other interface design factors did not significantly affect situation awareness; however, from Experiment 1 the head selection method was always seen in the combination of interface designs that gave the best results across all measures. User research on both selection methods by Kim, Lee, Jeon, and Kim (2007) has indicated that the head selection method affords enhanced immersion in virtual reality and could therefore explain the results found in Experiment 1. Participants were more immersed in the environment and could therefore build better situation awareness for the tasks they were asked to complete. The lack of significant findings for the movement method on the measures of situation awareness indicates that both the dashed and the teleport movement have their associated advantages. The teleport movement offers minimal discomfort in the users; however, the dashed movement offers optic flow information to build situation awareness as found in research by Kirschen, Kahana, Sekuler, and Burack (2000) where they examined participants' self-navigation with and without salient optic flow on a path recall task.

With regards to the second objective of the research to determine if interface design factors within a virtual environment directly affect the physical stress and mental workload of the operator, all three interface design factors (selection, movement, and search) showed significant results with regards to the physical stress measure. The head selection lowered the discomfort rating due to the ability to select objects without complex hand movements and a lower amount of modification to the visual scene, as found in research by Hinckley et al. (1994) and Argelaguet et al. (2012). The teleport selection lowered the discomfort rating as it did not cause the onset of cybersickness, as found in research by Davis et al. (2015). Lastly, the origin-based search lowered the discomfort rating as it created less disorientation and a constant cognitive map of the environment, as found in research by Wolbers et al. (2010).

The third objective to determine if a relationship existed between physical stress and mental workload to situation awareness was examined and found within the measure of physical stress, but not for mental workload. Physical stress was negatively correlated to how accurate people were to remember entity locations (i.e., the more discomforted the person was, the less they remembered in the memory task). This confirmed the results found by Sneddon et al. (2013) that the only significant predictor of situation awareness was physical stress. They determined after a multiple regression analysis that high physical stress produced low levels of situation awareness in offshore drilling crews. In real world settings, if an individual feels uncomfortable then they are less able to comprehend the environment they are in (e.g., air traffic controllers will not go to work if they are ill as it will impact their performance). Mental workload was not correlated to any measure of situation awareness or physical stress in Experiment 2. It is possible that the mental workload measures used in the present experiment were not sensitive enough to the slight changes caused by different interface designs and therefore no correlations emerged. Neither the selection, movement, or search method had any significant effect on the measures of mental workload used in the present experiments. However, all three interface design factors did have significant effects on the measure of physical stress; it is therefore possible that the different interface designs are too similar to yield changes to mental workload but that they still have the ability to affect situation awareness based on their effect to physical stress. Research by Perry, Sheik-Nainar, Segall, Ma, and Kaber (2007) examined the effects of physical stress on cognitive task performance and situation awareness. They had participants stand, walk, or jog on a treadmill to yield different levels of physical stress and made them perform simulated cognitive tasks that measured their situation awareness and their workload through the NASA-TLX. The results indicated that situation awareness decreased as physical stress increased, however cognitive task performance was not affected by changing the levels of physical stress. The results of the present experiments confirm the research by Perry et al. in showing that physical stress is correlated to situation awareness, but that measures of mental workload are not sensitive enough to the small changes in physical stress and therefore did not show any significant effects based on interface design.

4.2 Implications for Situation Awareness and Airborne Surveillance

Applications of immersive 3-dimensional (3D) display systems have been growing due to the ability of virtual reality (VR) platforms to display multiple streams of data in a novel way. The present research examined how VR interfaces can be used to enhance operator situation awareness in a real-world task: airborne surveillance. The tasks used in the present research mimicked common tasks required by operators in airborne surveillance (i.e., locating, selecting, and remembering objects that exist in 3D space). The results found in the present research indicate that VR interfaces should be designed carefully in order to improve operator situation awareness and physical stress and that three aspects of interface design are important to consider: object selection, operator movement, and search method. After researching and experimentally testing the different methods of selecting, moving, and searching for entities in an airborne surveillance task in VR, it is recommended that interfaces are designed where operators select objects using a head-gaze method, move towards objects through a teleportation method, and search for objects using an origin-based search method. Although all interface designs have associated advantages and disadvantages, the three suggestions mentioned above have been shown to improve situation awareness and reduce physical stress of the operator. Additionally, the present experiment has investigated the role that physical stress plays on operator situation awareness and has determined that when designing systems for airborne surveillance it is necessary to consider physical stress a factor of importance as it is directly linked to situation awareness, such that increasing physical stress decreases situation awareness.

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Appendices

Appendix A **SONA Posting**

Study Name: Object Selection and Operator Movement in Virtual Reality (VR)

Study Type: This is a standard lab study. To participate, sign up, and go to the specified location at the chosen time.

Pay: 2 percent course credit or $20

Duration: 120 minutes

Abstract: The purpose of this study is to see whether how you move around a virtual reality (VR) environment might affect your speed and accuracy when you perform tasks that require situation awareness.

Description: In this experiment, you will wear the Oculus Rift CV1 headset to view a visual environment in 3D VR (virtual reality). You will interact with and remember the location of objects in this VR environment. We are interested in the effects of blink (instantaneous) versus dashed (a few successive frames) teleportation in the VR environment. You will be asked to wear a small wristband that captures biometric data such as heart rate, temperature, motion, and skin galvanic response, and detect and respond to a tone played periodically during the task. The study will take approximately two hours to complete. This research was cleared by the Carleton University Research Ethics Board – B (Protocol Clearance #107662) February 2018. *****Physical Risks: Minimal chance of mild disorientation and/or nausea. ***** ****** Meet us on the second floor of VSIM Room 2201*****

Preparation: None.

Eligibility Requirements: Exclusion Criteria: Please do not sign up for this study if you are colour blind or if you have any known susceptibilities to virtual reality sickness (e.g., you regularly feel nauseous when playing virtual reality video games).

Researchers:
Danielle Krukowski

Kathy Van Benthem

Deadlines: Deadlines that occur on a Saturday or Sunday will be moved back to Friday

Sign-Up: 3 hour(s) before the appointment

Cancellation: 12 hour(s) before the appointment

Appendix B **Informed Consent Form**

Informed Consent

Project Title: Object Selection and Operator Movement in Virtual Reality (VR)
Faculty Sponsor: Dr. Chris Herdman, Department of Psychology, Carleton University, tel. 520-2600 x. 8122

The purpose of this informed consent form is to ensure that you understand both the purpose of the study and the nature of your participation. The informed consent must provide you with enough information so that you have the opportunity to determine whether you wish to participate in the study. This research was cleared by the Carleton University Research Ethics Board – B (Project Protocol Clearance ***#107662)*** *on Month Day, 2017. Please ask the researcher to clarify any concerns that you may have after reading this form.*

Research Personnel: In addition to the Faculty Sponsor named above, the following people are involved in this research and may be contacted at any time should you require further information about this study:

Name	Title	Department	Email	Phone
Kathleen Van Benthem	Research Fellow	Cognitive Science	kathy_vanbenthem@carleton.ca	520-2600 x. 2487
Danielle Krukowski	M.A. Student	Cognitive Science	daniellekrukowski@cmail.carleton.ca	520-2600 x. 2487

Other Contacts: If you have any ethical concerns with the study, please contact Dr. Andy Adler, Chair, Carleton University Research Ethics Board-B (by phone at 613-520-2600 ext. 4085 or via email at ethics@carleton.ca.

Purpose: The purpose of this study is to see whether how you move around a virtual reality (VR) environment might affect your speed and accuracy when you perform tasks that require situation awareness. We are also interested in how movement affects your experience. The results of this research will help us understand how features of VR technology support situation awareness. See Figure 1 for the Oculus Rift VR headset.

This work will compare the effect of two ways you can move in the VR environment– *blink* teleportation, which instantaneously transports you from one location to the next versus *dashed* teleportation, which shows your movement through a few quick visual frames. These movement varieties will be compared on a task where you interrogate a series of targets in a search environment and then remember their locations. Additionally, you will move through the VR space either sequentially (i.e., you move from one object to the next) or origin-based (i.e., you are automatically returned to a pre-determined point-of-origin after each object is interrogated). We are interested in your situation awareness and user experience during these virtual reality tasks.

Tasks: After providing informed consent and the experimenter has provided the task instructions you will complete approximately 10 minutes of training on the movement interfaces (blink and dashed teleporting). You will complete two practice scenarios – one that uses a *sequential* path (moving directly from one target to the next) and another that uses an *origin-based* path (you are always returned to the center of the environment before moving to the next target) to interrogate a small number (e.g., 4) of targets. All combinations of movement interfaces will be sampled in the practice scenarios.

You will then begin the first of eight experimental blocks: each block will consist of 18 interrogation trials, for a total of 144 trials. A memory task, relating to the position of the targets, and four brief questions about your experience will be administered at the end of each block. You are permitted a short break between each block.
You will also be asked to wear a small wristband (the Empatica E4) that captures biometric data such as heart rate, temperature, motion, and skin galvanic response. See Figure 4 for the Empatica E4 wristband.
Additionally, you will be required to make a button press in response to an auditory stimulus at random intervals during the experiment.

After the final experimental block has been completed, you will be debriefed by the experimenter and provided with the $20.00. This will mark the end of the experiment. The experiment is expected to take two hours to complete.

Figure 1. Oculus Rift Headset

Figure 2. 3D Interface (virtual number pad)

Figure 3. Oculus Touch VR Controllers

Duration, Locale & Compensation: Testing will take place in VSIM 2201 and will take approximately two hours to complete. You will receive $20.00 for your participation.

Potential Risks/Discomfort: Given that part of this study involves being immersed in VR, there is a mild risk of temporary disorientation and/or nausea. In the event that you begin to feel disoriented and/or nauseous, please inform the experimenter immediately. The experimenter will instruct you to remove the VR headset and to close your eyes for five minutes. During this time, the disorientation/nausea should go away. If the disorientation/nausea lasts beyond 30 minutes, you will be referred to Carleton University Health Services. You will be fully compensated ($20.00) for your participation even if the experiment has not been completed.

Anonymity/Confidentiality: All data collected in this experiment will be kept strictly confidential through the assignment of a coded number and securely stored on a local computer for a maximum of 10 years. This Informed Consent form will be kept for a maximum of five years before being destroyed. Your data will be used for research purposes and may therefore be presented and/or published. However, your data will be combined (averaged) with other participant data, thus your individual data will never be presented/published in any reports produced from this study.

Benefits: The recent expansion of VR capabilities has led to the opportunity to explore new approaches to visualizing data across a number of tasks. One area that is likely to benefit from advancements in VR technologies includes visual environments in which human operators must monitor and interact with multiple objects in complex and dynamic situations (e.g., air traffic control). The goal of this research is to inform the design and implementation of VR interfaces to maximize their potential.

Exclusion Criteria: Please do not participate in this study if you have colour blindness or if you know that you are susceptible to virtual reality sickness (e.g. you regularly feel nauseous when playing virtual reality video games).

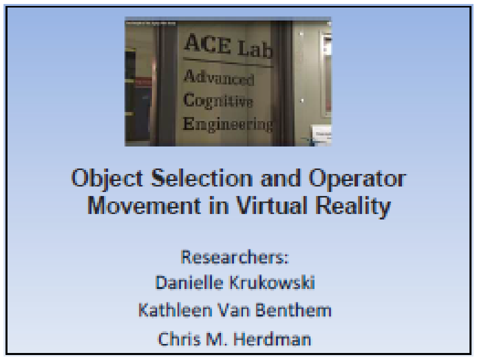
Right to Withdraw: You have the right to withdraw at any time during the experiment without academic penalty. You may not withdraw once you leave the experiment. Your participation in this experiment is completely voluntary.

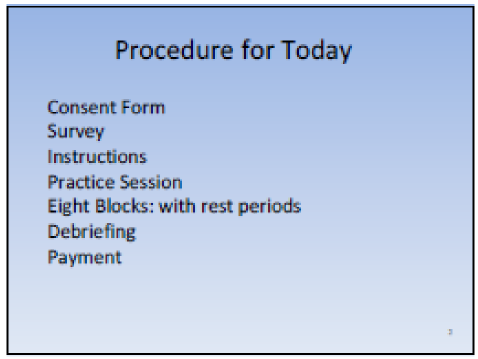
I have read the above description of the study on awareness in VR. By signing below, this indicates that I agree to participate in the study, and this in no way constitutes a waiver of my rights.

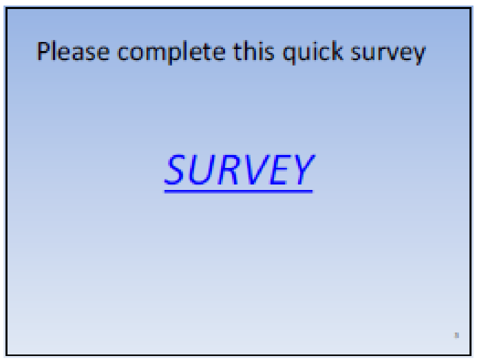
Name:______________________________ Date:____________________

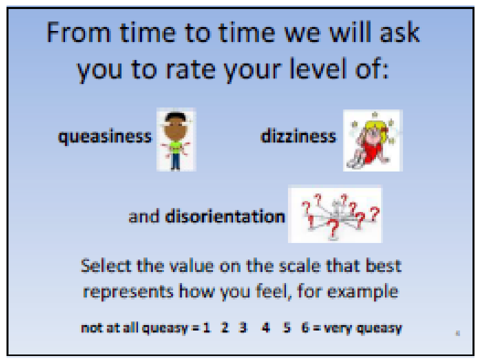
Signature:___________________________ Witness:_________________

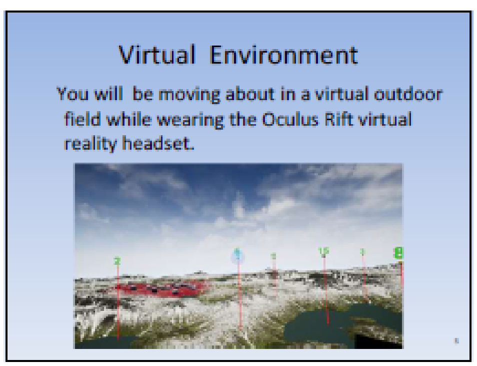
Appendix C **Experimental Instructions PowerPoint**

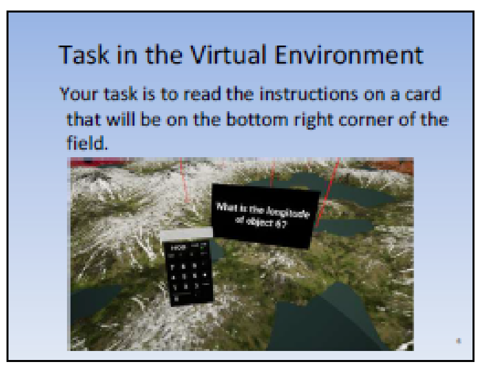








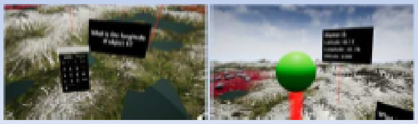




Tasks in the Virtual Environment

The instructions will ask you to find a numbered post (from 1 to 9) and then record some information attached to that post.

You should work as quickly as possible!



Tasks in the Virtual Environment

After you are finished locating the posts and recording the information requested, you will have a memory test.

You will be asked to place the correct shape associated with each numbered post.

Tasks in the Virtual Environment

YOU WILL COMPLETE THESE TASKS IN 8 DIFFERENT "SCENES" (BLOCKS).

IF YOU WISH, BETWEEN EACH BLOCK YOU CAN TAKE A BREAK, REMOVE THE OCULUS RIFT, AND SIT DOWN.

Remember to try your best… to the very end!

Thank-you for Participating!

Remember to do your best on all blocks,
and work as quickly as possible.
Let us know if you would like to sit or remove the Oculus Rift between the blocks.

Appendix D **Demographics Questionnaire**

Pre-Experimental Survey

* Required

Code *

[redacted]

Age *

[redacted]

Gender *

- o Female
- o Male
- o Prefer not to say

Other:

[redacted]

Dominant Hand *

- o Right
- o Left
- o Ambidextrous

What is your occupation? *

[redacted]

Do you have a history of motion sickness? *

- o No
- o Yes

Have you ever used the Oculus Rift or other Virtual Reality (VR) devices before? *

- o No
- o Yes

If so, how often do you use Oculus Rift or other VR devices?

- o Rarely
- o Monthly
- o Weekly
- o Daily

How often do you play non-VR video games? *

- o Never

- Rarely
- Monthly
- Weekly
- Daily

Appendix E **Debriefing Form**

Debriefing

Object Selection and Operator Movement in Virtual Reality (VR)

Thank you for your participation! This study investigates the advantages and potential drawbacks of selection methods, blink versus dashed teleportation, and sequential versus origin-based movement in VR environments. The purpose of this line of research is to inform the design and development of 3D/VR user interfaces so that operators can quickly and accurately interact with and remember information about objects in complex and dynamic environments (e.g., air traffic controllers). If you are interested in this area of research, then please see the following:

Earnshaw, R. A., Gigante, M. A., & Jones, H. (2014). Virtual reality systems. San Diego, USA: Academic Press.

This research was cleared by the Carleton University Research Ethics Board – B (Project Protocol Clearance #107662 on Month Day, 2017. If you have any ethical concerns with the study, please contact Dr. Andy Adler, Chair, Carleton University Research Ethics Board-B (by phone at 613-520-2600 ext. 4085 or via email at ethics@carleton.ca.

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Should you have any other concerns about this study then please contact any of the following individuals.