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An Exploration of the Feasibility of Functional Near-Infrared Spectroscopy as a Neurofeedback Cueing System for the Mitigation of the Vigilance Decrement

Gabriella Hancock
University of Central Florida

AN EXPLORATION OF THE FEASIBILITY OF FUNCTIONAL NEAR-INFRARED
SPECTROSCOPY AS A NEUROFEEDBACK CUEING SYSTEM FOR THE MITIGATION
OF THE VIGILANCE DECREMENT

by

GABRIELLA MARIE HANCOCK
B.S. University of Central Florida, 2008
M.S. University of Florida, 2011
M.S.I.E. University of Central Florida, 2014

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Major Professor: James Szalma

ABSTRACT

Vigilance is the capacity for observers to maintain attention over extended periods of time, and has most often been operationalized as the ability to detect rare and critical signals (Davies & Parasuraman, 1982; Parasuraman, 1979; Warm, 1984). Humans, however, have natural physical and cognitive limitations that preclude successful long-term vigilance performance and consequently, without some means of assistance, failures in operator vigilance are likely to occur. Such a decline in monitoring performance over time has been a robust finding in vigilance experiments for decades and has been called the vigilance decrement function (Davies & Parasuraman, 1982; Mackworth, 1948). One of the most effective countermeasures employed to maintain effective performance has been cueing: providing the operator with a reliable prompt concerning signal onset probability. Most protocols have based such cues on task-related or environmental factors. The present dissertation examines the efficacy of cueing when nominally based on operator state (i.e., blood oxygenation of cortical tissue) in a novel vigilance task incorporating dynamic displays over three studies. Results pertaining to performance outcomes, physiological measures (cortical blood oxygenation and heart rate variability), and perceived workload and stress are interpreted via Signal Detection Theory and the Resource Theory of vigilance.

I would like to dedicate my dissertation to my parents: Drs. Peter & Frances Hancock.

ACKNOWLEDGMENTS

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE: INTRODUCTION

Vigilance is the capacity for observers to detect the presence of critical signals over extended periods of time (Davies & Parasuraman, 1982; Parasuraman, 1979; Warm, 1984). Humans, however, have consistently demonstrated limited capacity for maintaining attention; and consequently, without some means of assistance, failures in operator vigilance are likely to occur. Such a decline in monitoring performance over time on watch has been a robust finding in vigilance experiments for decades and has been dubbed the vigilance decrement function (Davies & Parasuraman, 1982; Mackworth, 1948).

It is imperative to understand and seek ways to counteract such maladaptive performance, as vigilance represents a significant issue in a host of operational domains central to productivity, efficiency, and public health and safety (Warm, Matthews, & Parasuraman, 2009). Representative examples of such performance domains include: military surveillance (Gunn, Warm, Nelson, Bolia, Schumsky, & Corcoran, 2005), homeland security (Hancock & Hart, 2002), civil aviation (Wiggins, 2011; Wright & McGown, 2001), air traffic control (Hitchcock, Dember, Warm, Moroney, & See, 1999; Pigeau, Angus, O'Neill & Mack, 1995), airport baggage screening (Harris, 2002), diagnostic medical screening (Gill, 1996; Warm, Matthews, & Parasuraman, 2009), and anesthesia monitoring (Weinger, 1999; Weinger, Herndon, & Gaba, 1997).

Methodological Issues with Traditional Research Protocols

The importance of vigilance in myriad realms of performance was formally identified via laboratory experiments conducted over the last six decades. Unfortunately, the limited computational power in the seminal years of vigilance research may have led to the

establishment of protocols that are unrepresentative of many real-world performance contexts (Hancock, 2013). One of the first experimental procedures, conceived by Mackworth (1948), involved radar operators observing a clock-face for irregularities in the ticking of its hands for a period of two hours. Although this display contained representative elements of the real-world radar monitoring task of that time, the relatively simple displays employed in most laboratory studies of vigilance are less representative of modern day monitoring demands. Current real-world vigilance tasks often involve monitoring for stimuli that appear, retreat, or move dynamically within a display or an operational environment.

More recently, simulated air traffic control tasks involve surveying still images comprised of typical air traffic control routes that exemplify either safe traffic patterns (i.e., airplanes avoiding one another) or the critical signal of an impending collision (Hitchcock et al., 1999; Hitchcock, Warm, Matthews, Dember, Shear, Tripp, Mayleben, & Parasuraman, 2003). Again, in the operational environment, air traffic controllers use a dynamic display system that illustrates the spatial relations among aircraft in real-time, and operators monitor these relations rather than single still images of configurations from a bygone moment. Studying vigilance in an experimental paradigm that is more representative of the task should yield more valid conclusions regarding its time-course and successful mitigation. In sum, vigilance research has always relied on the most representative and technologically sophisticated simulation tools available, but current virtual reality systems are better capable of rendering the real world than ever before, complete with first-person perspective and dynamic movement as illustrated in the present protocol.

Mitigation Techniques: Cueing and Knowledge of Results

To compensate for the natural limitations of the human processing system and therefore safeguard effective performance to the greatest possible extent, researchers have explored several techniques to maintain vigilance. Two decrement mitigation techniques that have successfully supported superior performance outcomes are cueing and knowledge of results (KR; feedback) regarding the accuracy or speed of responses. Cueing (sometimes referred to as response prompting) involves the *a priori* presentation of a consistent and reliable prompt which alerts an individual of a forthcoming critical signal (Hitchcock, Dember, Warm, Moroney & See, 1999). The use of cueing influences performance, self-reported workload and stress, as well as physiological responses (Hitchcock, Dember, Warm, Moroney & See, 1999; Hitchcock, Warm, Matthews, Dember, Shear, Tripp, Mayleben, & Parasuraman, 2003; Thayer, Friedman, Borkovec, Johnsen, & Molina, 2000).

KR constitutes *post-hoc* feedback regarding correct detections, false alarms, and misses (Szalma, Hancock, Dember, & Warm, 2006; Szalma, Hancock, Warm, Dember, & Parsons, 2006), or the speed of responding (Church & Camp, 1965; McCormack, 1959; McCormack, Binding & McElheran, 1963). Both cueing and KR have been proven to be effective countermeasures against the vigilance decrement as reflected in consistently high correct detection rates (Annett & Paterson, 1967). However, a number of factors indicate that cueing is not only an effective method, but in many cases proves more effective than KR. Aiken and Lau (1967) advocated for the superiority of cueing in signal monitoring, particularly in performance scenarios where temporal demand is strenuous as it represents "a greater simplicity of procedure and economy of time" (pp. 339). Moreover, Annett and Paterson (1967) found that while both

techniques led to an increase in correct detections, KR likewise led to a greater proportion of false alarms; while cueing, in fact, yielded a smaller proportion of false alarms.

The novel aspect of the present work lies in investigating a different type of cue. Traditional cueing studies have used reliable environmental indicators relating to signal onset probability. For example, Hitchcock and colleagues (2003) presented an auditory warning (the word 'look' spoken by a digitized voice) that indicated a signal was likely to appear within the five trials following the cue. The present research, on the other hand, investigates cues based not on environmental indicators of signal likelihood which are often unpredictable, but rather cues nominally based on the physiological state of the observer's brain.

<u>Neurofeedback Cueing</u>

As discussed, cueing is an effective tool used to attenuate the vigilance performance decrement. However, Metzger and Parasuraman (2001) have argued that cues are only effective if they are reliable. Hitchcock and colleagues (2003) empirically supported this supposition by demonstrating that any deterioration in cue reliability was mirrored by an accompanying detriment in performance. Extremely reliable (100%) cues, however, helped maintain performance at an over 90% detection rate throughout the vigil.

To date, most cues in experimental protocols have been based on task factors (i.e., given the current circumstances, a signal is likely to appear in the near future). Nonetheless, predicting the future state of an environment is extremely difficult to do reliably, and any system that could do so, with high accuracy, would obviate the need for cues altogether. Cues based on an operator's cognitive or neurological state, however, may potentially prove reliable indicators of imminent lapse in vigilance.

20

Neurofeedback involves the willful manipulation of bodily functions via continual apperception of one's biological dynamics, such as brain wave activity (Raymond, Varney, Parkinson & Gruzelier, 2005). While most studies investigating the psychophysiological underpinnings of vigilance have concentrated on electroencephalography (EEG; Belyavin & Wright, 1987; Kamzanova, Kustubayeva, & Matthews, 2014), a growing body of research has investigated cerebral blood flow velocity and cortical blood oxygenation using functional near-infrared spectroscopy (fNIRS; de Joux, Wilson, Russell, & Helton, 2015). The fNIRS system's high spatial resolution combined with its ability to record the brain's metabolic versus electrical activity may serve as a more reliable long-term (vigil-length) cueing system when compared to transient EEG-waveforms.

<div align="center">Limitations of Previous Work</div>

In sum, given the computational limitations of presenting dynamic stimuli (i.e., stimuli that move or change in their organization over time) that were prevalent at the advent of vigilance research, early protocols generally relied on static displays. However, these static displays were not ecological valid with respect to of vigilance protocols as humans naturally perceive the world in a dynamic fashion (Hancock, 2013). Findings from early studies may be unrepresentative of vigilance performance in operational settings characterized by dynamic movement. To address this limitation, the current work experimentally manipulated stimulus dynamics to establish its effects on vigilance performance, as well as the subjective workload and stress that participants experience while performing a vigilance task.

Additionally, previous cueing studies have exclusively used cues based on the highly variable and difficult-to-predict external environment (i.e., cues regarding signal appearance).

For example, Hitchcock and colleagues (2003) provided participants with an auditory cue that indicated an increased likelihood of signal presence in the near future. However, while the experimenters could set this cue to be 100% reliable, there are real-world operational tasks in which the reliability of a cue cannot be known; for, if individuals were able to reliably predict future events in order to generate 100% reliable cues, cues would therefore (of course) be unnecessary. The present study therefore generated cues, not related to unpredictable environmental indicators of signal onset probability, but instead focused on the psychophysiological state of the human monitor. If the changes in psychophysiological measures (such as cortical blood oxygenation) that typically accompanying the decrement function can be identified before the performance decrement manifests, those measures could be used a cue to maintain effective performance.

<u>Purpose</u>

Given the aforementioned limitations of previous research, the purpose of this work is two-fold. Firstly, to determine whether the dynamism associated with stimulus presentation differentially affects vigilance performance. The second aim is to ascertain the effectiveness of nominal neurofeedback as a cueing tool to mitigate the vigilance decrement. These objectives were tested utilizing a video-game based, virtual simulation protocol (Szalma, Schmidt, Teo, & Hancock, 2014). Vigilance performance was evaluated via established Signal Detection Theory performance measures (i.e., correct detections, false alarms, and misses) as well as psychophysiological indicators of workload (i.e., heart rate variability). Dynamism was manipulated by presenting stimuli either statically (still images) or dynamically (video clips).

Cues were nominally based on cortical blood oxygenation in the prefrontal cortex as measured by functional near-infrared spectroscopy (fNIRS).

<div align="center">Current Studies</div>

Empirical studies have yet to fully explore: (1) how the dynamism of stimulus presentation (i.e., dynamic versus static stimuli) affects vigilance performance, or (2) whether cueing based on an operator's internal state is effective in mitigating the vigilance decrement. The present work is therefore comprised of a sequence of three experiments designed to address these research questions. The independent and dependent variables for these studies are summarized in Table 1.

Both the Pilot Study and Study 1 sought to establish the task parameters for the novel approach of experimental evaluation proposed in Studies 1 and 2. The Pilot Study sought to establish the psychophysical equivalency of the stimuli, ensuring that participants were able to detect the critical signals equally well in either the static or dynamic conditions. To this end, the experiment employed a two alternative forced choice task (2AFCT) to evaluate individuals' range of detection capabilities at low, moderate, and high levels of difficulty, as manipulated by stimulus exposure duration (i.e., 5, 3, or 1 seconds). Furthermore, the protocol of Study 1 called for participants to perform a vigilance task comprised of two counter-balanced task conditions, each consisting of a different mode of stimulus presentation. One contained exclusively still images and the other was composed of video clips. This experiment structure tested any influence of the mode of stimulus presentation (static versus dynamic) on performance in an abbreviated vigilance task. Results from the Pilot Study ensured that participants' vigilance performance and subjective experience were reflecting the mental demand of monitoring, rather

than the mental demand of signal discrimination/detection per se. Study 1 subsequently

investigated the effect of dynamism on vigilance performance, physiological functioning, and

cognitive and affective states.

Table 1. Manipulations and measures.

Study	Independent Variables	Manipulations	Dependent Variables	Measures
Psychophysical Equivalency Pilot Study	Duration	Stimulus Exposure Duration	Detection Performance	Correct Detections
	Low Medium High	5 seconds 3 seconds 1 second	Cognitive and Affective States	DSSQ Scores NASA-TLX Scores
1	Mode of Stimulus Presentation		Vigilance Performance	Correct Detections False Alarms
	Static Dynamic	Images Clips	Cardiac Activity	Heart Rate Variability
			Cognitive and Affective States	DSSQ Scores NASA-TLX Scores
2	Cueing		Vigilance Performance	Correct Detections False Alarms
	No Cueing (Control)		Cardiac Activity	Heart Rate Variability
			Cognitive and Affective States	DSSQ Scores NASA-TLX Scores

Study 2 tested whether nominal neurofeedback could serve as effective cueing to

counteract the vigilance decrement. The novel approach of this work lies in investigating

whether an established mitigation technique such as cueing maintains its efficacy if one changes

the nature of the cue from an externally-driven (i.e., state of the environment) to an internally-

driven (i.e., state of the operator) measure such as neurofeedback.

<u>Hypotheses</u>

Psychophysical Equivalency Pilot Study

<u>Detection Performance</u>

1) As the duration of stimulus presentation decreases, participants will exhibit a decline in correct detections and an accompanying rise in incorrect responses. Performance will be negatively related to duration, until performance approaches chance (50/50) in the 2AFCT.

<u>Cognitive and Affective States</u>

1) Participants will report higher levels of task engagement, distress, and worry as expressed by greater difference scores (Post-Test score - Pre-Test score) on the Dundee Stress State Questionnaire (DSSQ).

2) Upon task completion, weighted global NASA Task Load Index (NASA-TLX) scores will show high workload.

Study 1

<u>Vigilance Performance</u>

1) Participants will demonstrate superior vigilance performance when stimuli are presented in the dynamic video clips versus the static images as demonstrated by a greater number of correct detections and fewer false alarms.

<u>Cardiac Activity</u>

1) Heart rate variability difference scores (phasic – baseline) will be significantly smaller in response to the dynamic video clips vigil, compared to the static images vigil.

Cognitive and Affective States

1) DSSQ difference scores (post-pre) will reflect that participants experienced lower task engagement and greater distress following the vigil. Worry scores should not be affected by the form of stimulus presentation.

2) Participants will report high weighted global workload scores via the NASA-TLX after performing the task.

Study 2

Vigilance Performance

1) Participants who receive the cueing nominally based on neurofeedback will outperform their non-cued counterparts by exhibiting a greater number of correct detections as well as fewer false alarms during the vigil.

Cardiac Activity

1) Heart rate variability difference scores (phasic – baseline) will be significantly smaller during the vigil for participants who were cued compared to those participants who were not in the cued condition.

Cognitive and Affective States

1) Participants in the non-cued condition will report higher levels of distress than the cued participants as measured by DSSQ difference scores. Worry scores should not be affected.

2) Participants in the cued condition will report greater task engagement than non-cued participants when DSSQ task engagement scores are compared.

3) Participants in the cueing condition will report lower weighted global workload scores when compared to non-cued participants as measured by the NASA-TLX. These effects are also expected to occur for the TLX subscales, with mental demand and frustration contributing most to the workload of the task.

CHAPTER TWO: REVIEW OF LITERATURE

Vigilance has been defined as the ability to maintain attention over extended periods of time while responding to infrequent and unpredictable signals within the context of an imposed monitoring and detection task (Davies & Parasuraman, 1982; Warm, 1984; Warm, Parasuraman & Matthews, 2008). The phenomena of vigilance, especially the performance decrement, have proven of great theoretical and practical interest to researchers in a variety of performance domains (i.e., military, medicine, security, etc.) for decades (Gunn et al., 2005; Hancock & Hart, 2002; Weinger, 1999). Despite the progress of the past sixty years, there remain unexplored issues that have the potential to alter the effectiveness, efficiency, and safety of humans engaged in the aforementioned pursuits. The main purpose of the present work is two-fold: 1) to investigate the effects of static versus dynamic stimulus presentation on vigilance performance and its underlying physiological indicators (i.e., heart rate variability and blood oxygenation), and 2) to investigate whether cues based on nominal neurofeedback (of cortical blood oxygenation using functional near-infrared spectroscopy) can be used as an effective cueing tool to attenuate the vigilance decrement.

This review begins with a definition of the term vigilance and a summary of different opinions regarding the theoretical distinction between vigilance and the construct of 'sustained attention'. A brief exploration of the historical context of vigilance research is then provided. To elucidate empirical findings concerning the effects of vigilance on subjective and objective performance outcomes, this review presents an overview of Signal Detection Theory which defines its relevant terms. Moreover, the strengths and weaknesses of traditional methodological

protocols in vigilance and proposed changes to such protocols are presented. This is then followed by a discussion of the nature of psychophysiological measures and their contributions to the understanding of vigilance. Next follows a discourse on the two major alternative models for explaining characteristic vigilance performance, and how vigilance performance leads to specific changes in the hemodynamics and blood oxygenation levels of the brain. Vigilance decrement mitigation techniques are then subsequently described, the efficacy of neurofeedback training is reviewed, and finally, the feasibility of neurofeedback as a real-time cueing system is explored.

<div align="center">Vigilance or Sustained Attention?</div>

In previous research, the term 'vigilance' has often been used interchangeably with the term 'sustained attention' (e.g., Sarter, Givens & Bruno, 2001). However, there have been recent efforts to distinguish between the two constructs (Hancock, 2013). Some researchers argue that what has been considered 'vigilance' and the vigilance decrement are fundamentally artefacts of suboptimal and unrepresentative laboratory-based experimental design. In contrast, 'sustained attention' is a naturally-occurring capacity employed by organisms in their attempts to adapt to various environmental demands (Hancock, 2013). In other words, 'vigilance' is an *imposed* monitoring task, while sustained attention is an *intrinsic* capability elicited by situational demands or the goals of the organism.

While this perspective concentrates on the genesis of the phenomenon, there is another differentiation of the terms. The definition of sustained attention hinges on individuals' readiness to detect signals, therefore obviating the need for an overt response (Hancock, 2013). From this perspective, a participant may therefore perceive a rare signal and the criteria for sustained

attention are subsequently met. However, vigilance necessitates a behavioral *response* as a consequence of perceiving a signal (i.e., a button press, a mouse click, a verbal report, etc.), hence the reason it has been designated vigilance *performance* in lieu of merely 'attention'. To summarize, researchers have made numerous, theory-driven attempts to differentiate vigilance from sustained attention; however, for the purposes of a review of literature, the terms are largely used synonymously (in both theory and application) and are therefore both terms employed here.

The Historical Context of Vigilance Research

The problem of vigilance has been of great concern to psychologists (especially those in experimental and human factors psychology) since before the Second World War (Mackworth, 1948, 1950). The majority of research concerning vigilance was conducted in reaction to the challenge of radar monitoring during World War II (Warm, 1984). Perhaps due to its origins in warfare, the main emphasis of vigilance research and its application have been firmly entrenched in military contexts in the intervening decades. Researchers have nonetheless observed reliable physiological and behavioral outcomes associated with vigilance across numerous performance domains. Notable and contemporary domains of interest that have benefited from vigilance research include air traffic control (Brookings, Wilson, & Swain, 1996; Pigeau, Angus, O'Neill & Mack, 1995), transportation (Bergasa, Nuevo, Sotelo, Barea, & Lopez, 2006), and medical screening (Gill, 1996; Scott, Rogers, Hwang, & Zhang, 2006; Weinger, 1999; Weinger, Herndon, & Gaba, 1997).

Signal Detection Theory

Peterson, Birdsall and Fox (1954) developed the first mathematical models establishing the probabilities of signal identification amongst noise that would become known as Signal

Detection Theory (SDT). The goal of SDT is to model human decision-making ability, such as the capacity to recognize an object or pattern of data of interest (i.e., a signal) amongst extraneous or distracting information (i.e., noise), when confronted with ambiguous conditions (Green & Swets, 1966).

An important assumption underlying SDT is that an individual actively makes judgments concerning signal versus noise distinctions when evaluating ambiguous information. Signal detection performance outcomes (i.e., judgments) may therefore fall into four categories: hit (H), false alarm (FA), miss (M) and correct rejection (CR). A "hit" is said to have occurred when a participant indicates the presence of a signal and a signal is indeed present in the environment. A "false alarm" occurs when a participant identifies an event as a signal when, in fact, none exists. A "miss" occurs when an individual fails to respond to a presented signal, and a "correct rejection" entails a participant identifying an event as a non-signal when, in fact, there is none.

SDT provides procedures for the computation of an individual's sensitivity index that takes into account both the individual's perceptual acumen as well as their bias towards one kind of response versus another (i.e., liberalism versus conservatism in identifying signals). Sensitivity refers to a person's perceptual capacity to detect a target stimulus from among extraneous noise. Bias is the individual's likelihood of providing one kind of response versus the other (i.e., the general tendency to give either a present or not-present response).

One commonly employed sensitivity index is d' (d-prime); it represents the distance between the means of the overlapping signal and noise likelihood distributions as reported in standard deviation units (Tanner & Swets, 1954; and see Figure 1). The values of d' conceivably span the range from 0 to infinity, although in most research, the values rarely exceed 4 or 5

(Macmillan & Creelman, 2005). A zero value of d' therefore indicates a diminished capacity to distinguish signal from noise (indicating performance is due to chance); while larger scores for d' represent a higher capacity for such distinction (Mackworth & Taylor, 1963; Stanislaw & Todorov, 1999; Tanner & Swets, 1954).
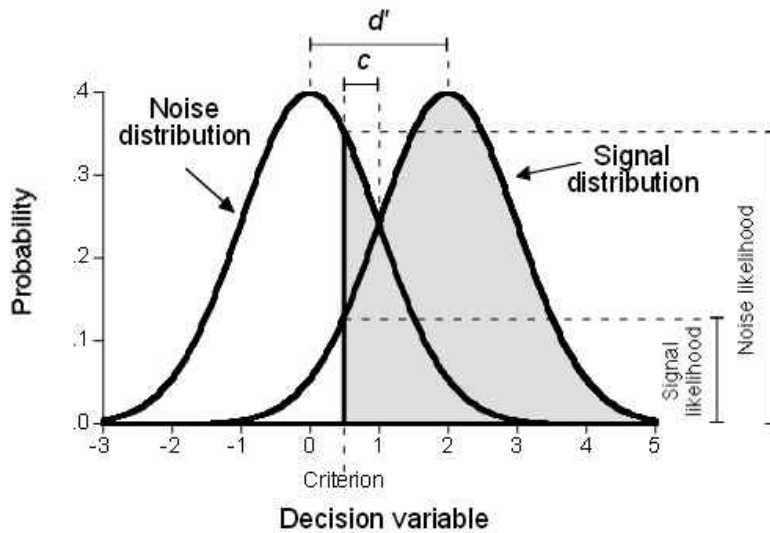
Figure 1. The likelihoods used for response bias calculation (here represented as c and referred to in the discussion as β) as well as d´ are illustrated in the different distributions of signal versus noise trials. Taken from Stanislaw & Todorov (1999). Reprinted with permission.

An individual's detection performance depends not only on their perceptual abilities, but also on their response bias referred to as β (beta) in the literature. β is based on a ratio of the likelihood of obtaining a certain specified value on a signal trial divided by the likelihood of obtaining the same, certain specified value on a noise trial. Therefore, when respondents are not biased to respond one way or the other, β = 1. When ratio scores are less than 1, respondents are more likely to attest to the presence of a signal (i.e., they set a lenient criterion); whereas a ratio greater than 1 indicates that participants are more likely to refrain from tentatively identifying a stimulus as a signal (i.e., they adopt a more conservative criterion; Stanislaw & Todorov, 1999).

Using these statistically derived measures, researchers have quantified vigilance performance tested via a host of different experimental protocols.

<center>Traditional Vigilance Paradigms: Taxonomies & Experimental Protocols</center>

A short exploration of the simultaneous versus successive vigilance task is herein presented to provide a theoretical foundation on which the current experimental protocol was based, and to impart justification for the choices in the experimental design.

A vigilance taxonomy with regard to discrimination tasks, designating them as either successive or simultaneous, was developed by Parasuraman and Davies (1977). A number of studies have identified this discrimination type as a key factor in distinguishing successful versus unsuccessful vigilance performance (Nuechterlein, Parasuraman & Jiang, 1983; Parasuraman, 1979; See, Howe, Warm & Dember, 1995). Parasuraman, Warm and Dember's (1987) resource-centric view proposed that successive tasks are more cognitively demanding than simultaneous tasks as they tax participants' limited short-term memory capacity. In other words, it requires more processing capacity to compare a stimulus to an image held in memory (successive task), than to compare a stimulus to another stimulus element in the same display (simultaneous task).

Successive tasks involve comparisons between two independent and sequentially presented stimuli; to make a decision, the participant must hold the image of either the signal or non-signal stimulus in working memory and then compare it to the subsequently presented stimulus. Successive tasks therefore demand absolute judgment. A classic example of such a successive task is illustrated in the protocol of Becker, Warm, Dember and Hancock (1991; and see Figure 2). In this study, participants were seated in front of a video display terminal onto

<center>33</center>

which were projected sequential images of vertical lines. Participants were expected to compare the line lengths from successive images, which could differ by up to 3mm to denote a signal.
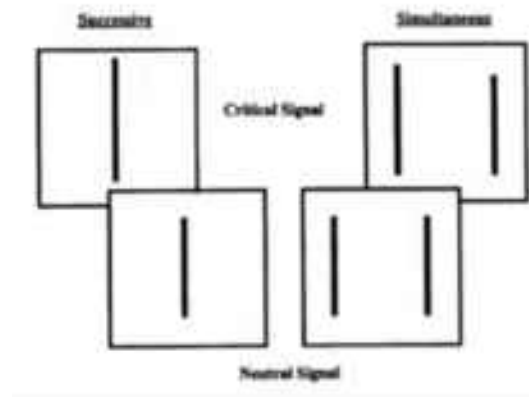
Figure 2. Stimuli used by Becker and colleagues (1991) to investigate simultaneous versus successive task type effects on vigilance performance. Taken from Szalma et al. (2014). Reprinted with permission.

Simultaneous tasks, on the other hand, present both stimuli in tandem. That is, observers compare elements within the same presented stimulus to one another when making a decision. Perceiving both stimuli simultaneously allows the individual to make a comparative (rather than an absolute) judgment regarding the presence of a signal. The experimental protocol used by Hitchcock and his colleagues (2003) is an example of such a simultaneous task and is depicted in Figure 3. Here, the stimuli are comprised of air traffic patterns resembling a target. The center (or bull's eye) represents an airport and three concentric circles surrounding the center represent landing airspace. Two lines, representing the differential flight lines of two separate aircraft, traverse this space toward the center. Participants are asked to respond when the two flight lines are in-line with each other, indicating the critical signal of a potential mid-air collision (as the

flight paths will overlap). Non-signals constituted any instances where the two flight lines show

no opportunity for meeting or overlapping each other.

Neutral Event (Safe) Stimuli

Northwest/Southeast Flight Paths

Southwest/Northeast Flight Paths

Critical Event (Collision Path) Stimuli
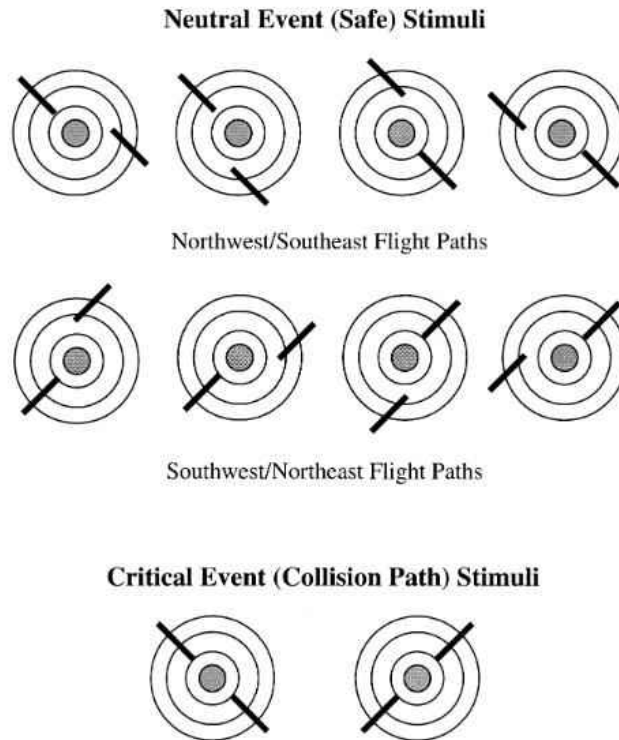
Figure 3. The static stimuli used to simulate an air traffic control task as used by Hitchcock and colleagues (1999). Reprinted with permission.

Regardless of whether the stimuli are presented successively or simultaneously, the

majority of these tasks share the common drawback that all stimuli are displayed as static

images. Traditional experimental protocols have, to date, lacked the technological sophistication

to present dynamic environments. Instead, they have relied on the types of static stimuli

described above. However, humans perceive the world dynamically and empirical results

obtained using traditional static protocols are subsequently difficult to generalize beyond

laboratory settings. The ecological validity of vigilance research may therefore improve if researchers adopt an experimental paradigm wherein stimuli are presented in a dynamic fashion.

<u>Static versus Dynamic Stimulus Presentation</u>

The above discussion illustrates how traditional methodological protocols in vigilance research have been constrained to the presentation of static signals. Far from being an experimental oversight, lack of dynamism in classic experiments was instead most likely due to limited technological capabilities; displays of the era almost exclusively presented stimuli via still images. Further, discrete trials also provide experimental control as well as convenient units through which to categorize and determine performance level. Modern technology, however, has now developed to such an extent so as to transcend this methodological obstacle in both research and operational settings. Computer hardware and software are now capable of constructing dynamic (i.e., movement-based) and interactive scenarios for stimulus presentation and detection which may prove more representative of sustained attention tasks in real-world, operational settings (see Teo, Schmidt, Szalma, Hancock & Hancock, 2012; Teo, Szalma, Schmidt, Hancock & Hancock, 2012; Szalma, Schmidt, Teo, & Hancock, 2014; and see Figure 4).

An additional benefit of dynamic stimulus presentation, such as that afforded by video game-based platforms, includes the ability to depict first-person perspective movement through virtual environments (Teo, Schmidt, Szalma, Hancock & Hancock, 2012; Teo, Szalma, Schmidt, Hancock & Hancock, 2012). A supplementary layer of realism is integrated into the participants' experience via this first-person perspective motion as they are able to move throughout the virtual environment as though seen through their own eyes, as opposed to watching an avatar of themselves interact with the environment. Such a configuration therefore more successfully

incorporates the potential advantages of the human visual system into the virtual world in which performance is studied when compared to a static display. Consequently, presenting different types of stimuli to the visual system should theoretically produce discrepant electrical and metabolic activity in the brain as it interprets these static versus moving stimuli. In order to assess such differences, a variety of physiological measurement techniques can be adopted, and thus the main physiological measures of electrical activity (electroencephalography) and metabolic activity (positron emission tomography, transcranial Doppler sonography, functional magnetic resonance imaging, functional near-infrared spectroscopy) in the brain are herein examined alongside psychological changes associated with vigilance performance.

Figure 4. An illustrative example of the first-person perspective afforded by the dynamic stimulus presentation in Virtual Battlespace 2 software. Taken from Szalma and colleagues (2014). Reprinted with permission.

Psychological and Physiological Outcomes of Vigilance Performance

Researchers have investigated a variety of vigilance outcomes including performance and subjective reports of stress and workload. This body of work has established that participants experience significantly altered psychological states as the result of engaging in a vigilance task.

Prior research has established that vigilance can be "stressful" (Hancock & Warm, 1989; Warm, Parasuraman & Matthews, 2008), and that it can impose substantial workload on observers (Warm, Dember, & Hancock, 1996). More specifically, participants have reported greater levels of boredom, irritation, fatigue (Warm, 1993) and frustration following completion of a vigil (Szalma et al., 2004).

Chief amongst the performance outcome measures has been a consistent phenomenon known as the vigilance decrement. This is a decreasing correct detection rate stemming from the degradation in the capacity for vigilance and is illustrated in Figure 6 (Mackworth, 1948; Parasuraman, 1986). The seminal work on the vigilance decrement was reported by Norman Mackworth on sonar and radar operators enlisted in the Royal Air Force (Mackworth, 1948; 1950). Simulating a sonar/radar detection task, Mackworth designed what is now known as the "Mackworth Clock" task (see Figure 5). This image depicts the featureless, white clock face that was presented to participants. Rotating around this clock face was a singular black pointer which would make a full 360° rotation in 100 seconds; each second, the pointer would move one corresponding space.

Participants were instructed to watch this process and to indicate when the pointer progressed by two spaces instead of one (a 'double-jump') by pressing a response key. The signal was presented twelve times every 20 minutes. Over the two-hour vigil, Mackworth observed that the rate of missed signals almost doubled from 15% in the first half hour to 28% in the last (fourth) half hour (and see Figure 2-6). Building on Mackworth's findings, Teichner (1974) reported that the vigilance decrement manifests as early as fifteen minutes into the vigil,

and even more drastically, Jerison (1963) observed a performance decrement within only the first few trials.

Figure 5. Pictorial representation of the Mackworth Clock Task (Mackworth, 1948; 1950). Taken from Szalma, Schmidt, Teo, & Hancock (2014). Reprinted with permission.

Research efforts over the past thirty years have forwarded a different perspective, advocating that the onset of the vigilance decrement relies less on time per se than it does on the amount of mental workload imposed by the task. Neuchterlein, Parasuraman and Jiang (1983), for example, reported evidence of a performance decrement within only five minutes of the outset of the vigil when signal conspicuity was diminished, forcing participants to expend additional mental resources to distinguish signal from noise. Temple and his colleagues (2000) similarly manipulated task difficulty by modifying the contrast ratio of the signal and noise stimuli. Their results indicated a more drastic decline in performance for the participants in the condition of greater difficulty within only twelve minutes. Such results are in keeping with the direct-cost view of vigilance, which maintains that engagement in vigilance tasks entails high

cognitive load and produces significant stress (Warm, Parasuraman & Matthews, 2008; Hancock & Warm, 1989).
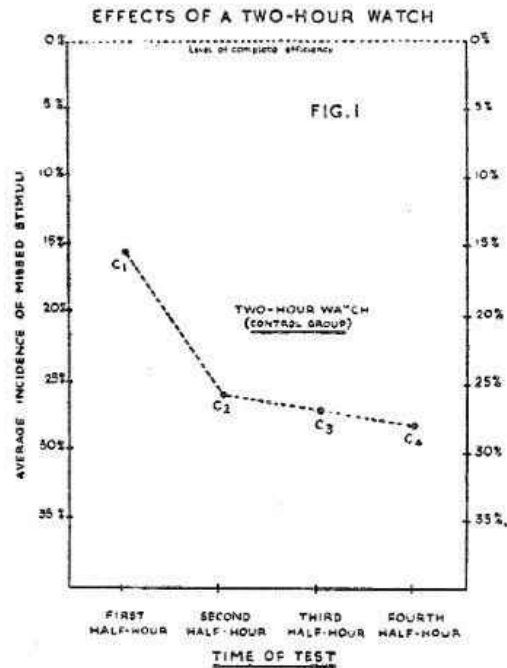
Figure 6. Visual representation of the increase in missed signals (and consequent decline in correct detections) that characterize the vigilance performance decrement. Taken from Mackworth (1948, pp. 8). Reprinted with permission.

Direct-Cost versus Indirect-Cost Models of Vigilance

In recent years, two competing theories have sought to explain these aforementioned effects of high workload and task-induced stress that accompany any vigilance task: the direct-cost and indirect-cost models (Alikonis, Warm, Matthews, Dember, Hitchcock, & Kellaris, 2002). The direct-cost model was derived from an attention resource theory of human processing (Fisk & Scerbo, 1987; Fisk & Schneider, 1981; Kahneman, 1973) and holds that high workload and stress are the result of cognitive resource depletion caused by the immediate task demands of monitoring and decision-making (Hancock & Warm, 1989; Warm, Dember, & Hancock,

1996).The indirect-model, conversely, argues that heightened workload and stress measures are unrelated to task elements, but rather stem from active efforts to counteract the aversive experience of monotony that is concomitant with vigilance performance (Scerbo, 1998b). Research encompassing behavioral, subjective, and neural phenomena has provided strong empirical support for the direct-cost model of vigilance performance.

Parasuraman, Warm, and Dember (1987) found that increasing the demand for information processing (by asking participants to multitask) led to larger detriments in performance in successive relative to simultaneous tasks, as successive tasks require more attentional resources (i.e., short-term memory). Warm, Dember, and Hancock (1996) reviewed research which established that perceived workload increases linearly over the course of the vigil. Grier and colleagues (2003) studied two types of vigilance protocols, each designed to test the effortful attention versus mindlessness contentions of the competing models. The authors' observed high workload and high stress scores support the direct-cost view of continual information-processing and consequential depletion of attentional resources over that of mindlessness (and see Helton, Hollander, Warm, Matthews, Dember, Wallaart, Beauchamp, Parasuraman, & Hancock, 2005; Helton & Warm, 2008).

Research to date that has attempted to link this conceptual depletion of resources to the performance decrement using psychophysiological measures and brain imaging techniques has been problematic. Coull, Frackowiak and Frith (1998) implicated both the right frontal and parietal cortices as the neuroanatomical epicenter for selective responding over time. Paus and colleagues (1997) similarly observed reductions in cerebral blood flow in both the frontal and parietal cortices as a function of time-on-task, as shown in Figure 7. However, there are two

significant methodological issues to consider, namely that the sample sizes for these studies were

quite small (six and eight, respectively) and both were conducted exclusively on males.
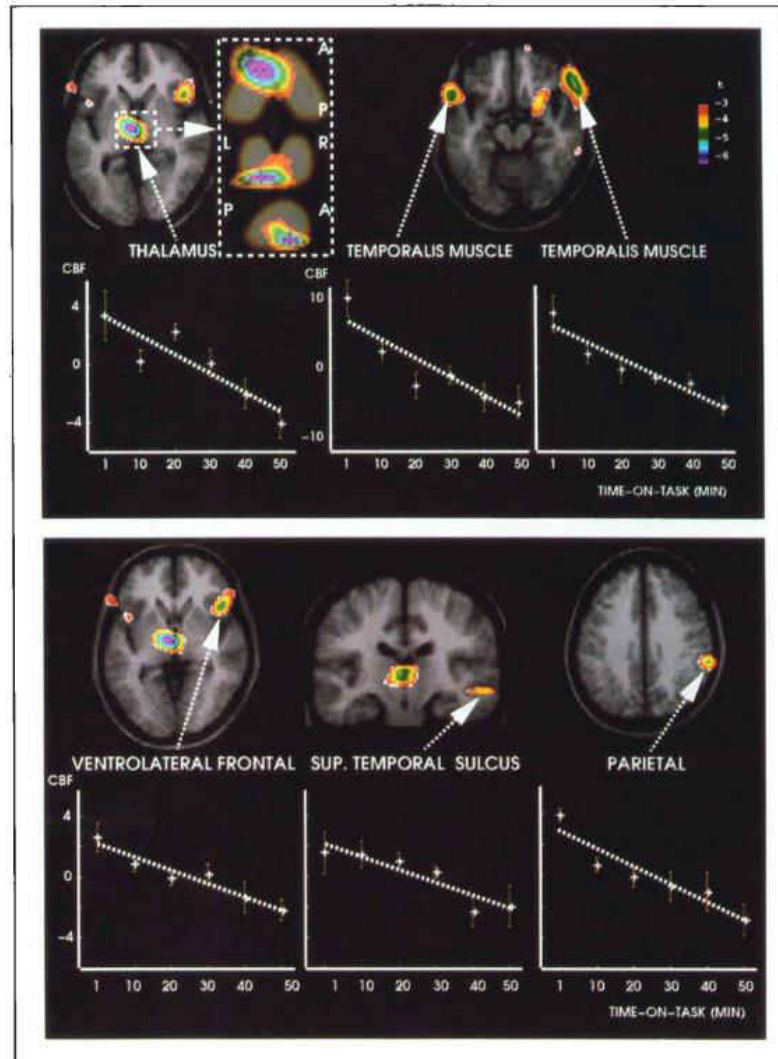
Figure 7. Cerebral blood flow values (relative to baseline) plotted against time-on-task in an auditory vigilance task. Taken from Paus et al. (1997). Published by MIT Press and reprinted with permission.

Studies that used positron emission tomography (PET) to observe the metabolic

ramifications of vigilance performance such as increased cerebral blood flow (Parasuraman &

Caggiano, 2005) are problematic for two significant reasons. Firstly, these techniques are cost-

prohibitive for recording extended vigils. As a result, the Coull study only lasted 18 minutes and may therefore prove unrepresentative of real-world vigilance performance. Secondly, the data collection process for these techniques restricts participants' movements, again compromising the generalizability of the observed results (Warm, Parasuraman, & Matthews, 2008).

Despite the issues inherent to these research efforts, they have provided support for the direct-cost (resource) model of vigilance, and have provided insights into the neural and metabolic mechanisms underlying vigilance performance. Building on these findings, more recent research has provided additional insight concerning psychophysiological functioning during vigilance by adopting measures and methods that minimize the confounds of cost and motion-restriction. These primarily feature changes in hemodynamics and blood oxygenation as measured by transcranial Doppler sonography (TCD) and functional near-infrared spectroscopy (fNIRS).

<div align="center">Hemodynamic & Blood Oxygenation Variations in Vigilance</div>

In conjunction with the aforementioned PET studies, extensive experimental results (Helton et al., 2007; Warm & Parasuraman, 2007) and reviews of the extant literature (Warm, Matthews, & Parasuraman, 2009) have established that 1) the vigilance performance decrement is associated with a corresponding decline in cerebral hemovelocity, and 2) the control of vigilance performance emanates primarily from the right hemisphere of the brain.

In keeping with the direct-cost model, decreased cerebral blood flow velocity (as an indicator of metabolic resource depletion) is greater in successive relative to simultaneous task performance (Mayleben et al., 1998; Schnittger, Johannes, Arnavaz, & Munte, 1997). Figure 8

illustrates the negative linear relationship between blood flow velocity and time on task over the

course of a vigil.
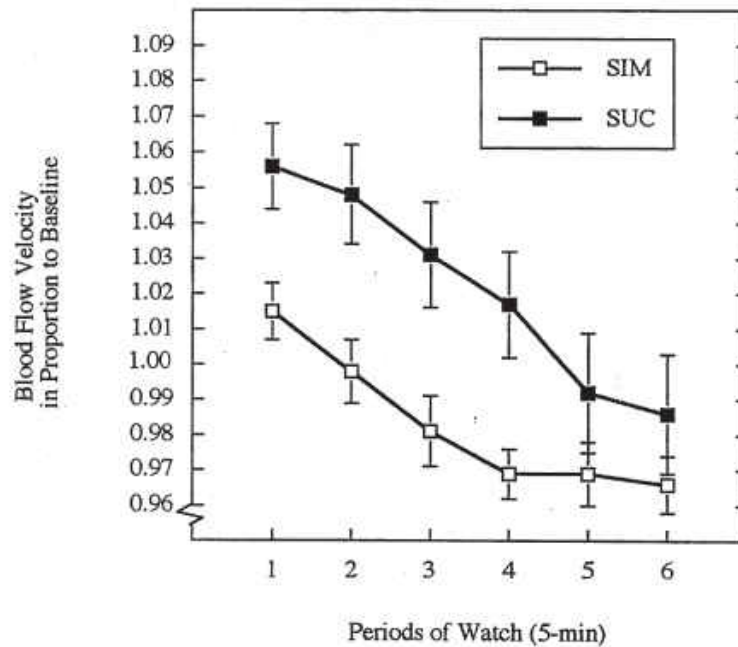
Figure 8. Mean cerebral blood flow velocities (in proportion to baseline values) as a function of
time on watch. Values presented for both simultaneous (SIM) and successive (SUC) tasks. Based
on Mayleben and associates (1998). Taken from Warm, Matthews, & Parasuraman (2009).
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Figures 8 and 9 both show the type-of-task effect that also follows from the direct-cost

model. The successive tasks that entail a greater amount of information-processing (and

consequently a greater need for metabolic resources) have a greater proportion of cerebral blood

flow velocity, when compared to simultaneous tasks (Figure 8), especially as it pertains to the

right hemisphere (Figure 9).
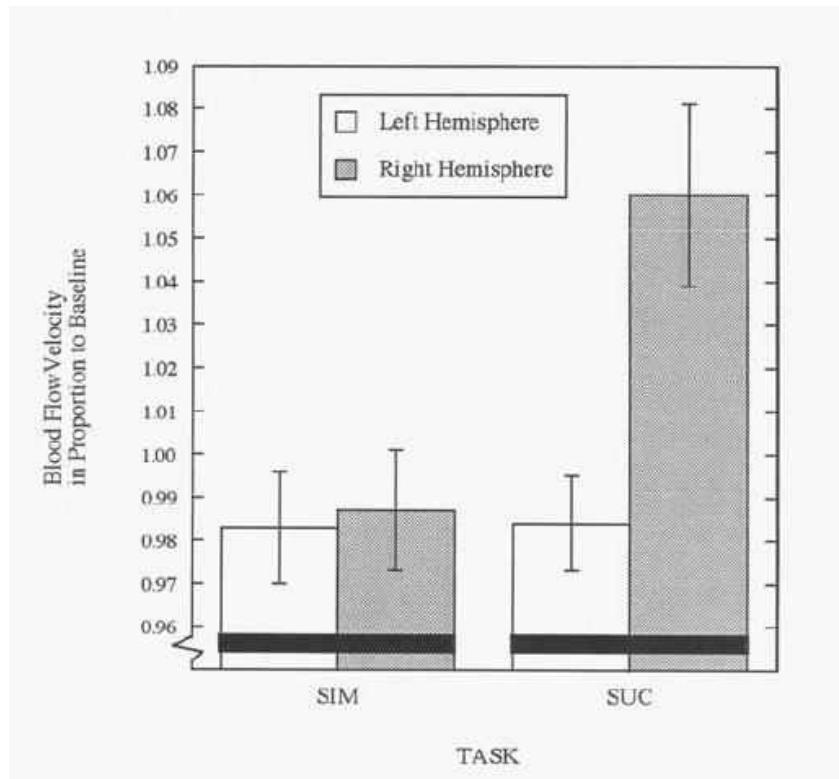
Figure 9. Mean cerebral blood flow velocity in response to simultaneous (SIM) and successive (SUC) tasks in the left versus right hemispheres. Based on Mayleben et al. (1998). Taken from Warm, Matthews, & Parasuraman (2009). Published by APA and reprinted with permission.

In addition to changes in how fast blood is flowing through cerebral blood vessels, experimenters have also investigated the amount of oxygen in cortical tissues. Functional near-infrared spectroscopy can detect the oxygenation levels of the blood supplying brain tissue during the performance of a vigilance task (Warm & Parasuraman, 2007). Studies have shown that cortical tissue oxygenation increases in response to the information-processing demands imposed on the cognitive system (Punwani et al., 1998; Toronov et al., 2001). Helton and colleagues (2007) observed significantly higher blood oxygen saturation levels in the right

hemisphere during an abbreviated (12 minute) vigil, that correspond to the characteristic decline in performance over time (and see Figure 10).
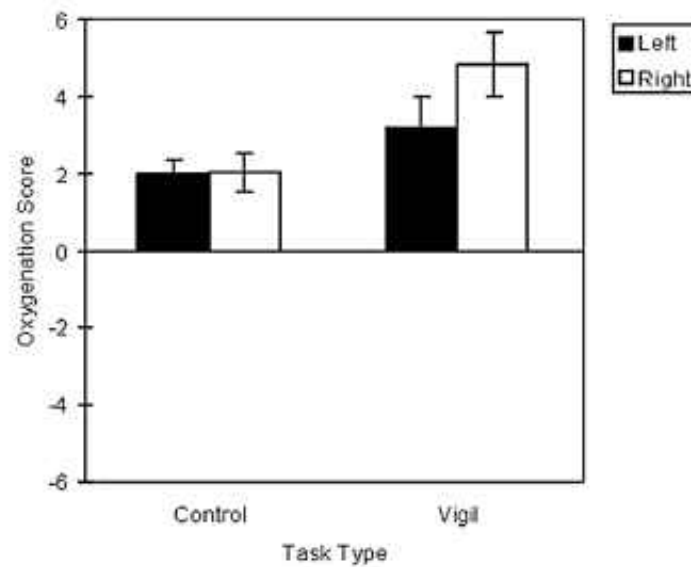
Figure 10. Mean blood oxygenation scores (relative to baseline functioning) by type of task (vigil vs. control – staring at the display) and cerebral hemisphere (left vs. right). Taken from Helton et al. (2007). Reprinted with permission.

<u>Vigilance Decrement Mitigation Techniques</u>

Various techniques have been used to support effective vigilance performance with varying degrees of success. Proposed methods include replacing the human monitor with automation (technology-centric techniques; Dutta, Grimmer, Arora, Bibyk, & Culler, 2005). However, some researchers maintain that the human represents an indispensable component of the vigilance system, and should therefore remain in the loop with technological support (operator-based techniques; Parasuraman, 1987).

Technology-Centric Techniques

One school of thought advocates replacing the human monitor altogether with automated systems (especially for improvised explosive device (IED) detection) such as wireless sensor networks or thermal infrared systems. Wireless sensor networks are systems designed to detect ferromagnetic materials (common materials in IEDs) within a certain three-dimensional space with the aid of magnetic sensors (Dutta et al., 2005). However, the sensors can only monitor a physical area of fixed and limited dimensions (Dutta et al., 2005) which can minimize its utility for vigilance activities that must be performed while in motion, such as mounted and dismounted military patrols. Moreover, the device may be overly sensitive to the amount of non-signal-related magnetized metal in the area leading to an increase in false alarms. Conversely, critical signals may have insufficient levels of ferromagnetism to register with the system, leading to missed targets. Thermal infrared systems also represent a suboptimal solution to the problem of poor detection (Aguilar et al., 1998) as they are extremely dependent on unpredictable weather patterns and climate conditions.

The human is therefore a necessary component in any system that depends on perception and sense-making (Parasuraman, 1987). Future efforts should therefore seek to marry the strengths of both operator and automation in order to construct an effective system for maintaining vigilance performance (de Winter & Dodou, 2011; Fitts et al., 1951; Hancock & Scallen, 1996). A truly effective system will consequently optimize the operator's mental workload rather than minimizing it. Chambers and Nagel (1985) demonstrated that assistive automation that minimized the human factor in task performance led to feelings of complacency and boredom, resulting in ineffective monitoring performance. The key is then to design a

system wherein the automation fulfills routine duties, acting as an assistant to the cognitively engaged, decision-making human operator (Parasuraman, 1987).

Operator-Centric Techniques

Perhaps the most intuitive countermeasure is to allow the human monitor to periodically disengage from the task over the course of the vigil (Ariga & Lleras, 2011). However, by instituting cognitive breaks, one runs the risk of missing critical signals during the process of substituting one monitor for another. Therefore, research has sought to find the means of supporting rather than replacing the human. Two successful strategies include cueing and knowledge of results (KR) or feedback.

Cueing

Cueing involves the participants receiving a consistent and reliable prompt which is meant to alert them of a forthcoming critical signal (Hitchcock, Dember, Warm, Moroney & See, 1999). Implementing cues significantly affects both objective and subjective performance outcomes as well as physiological functioning.

The implementation of cueing leads to superior performance in two critical aspects: 1) cued participants make significantly more correct detections (Hitchcock et al., 1999; Kamzanova, Kustubayeva, & Matthews, 2014) and 2) false alarm rates are consistently lower when participants have reliable cueing (Hitchcock et al., 2003). Such results for cueing are surprising and encouraging given that cued participants performed even better than participants who received KR (Hitchcock et al., 1999). In fact, reliable cues led participants to maintain a performance level of higher than 95% accuracy over an extended period of time as illustrated in Figure 11 (Hitchcock et al., 1999). Cueing is therefore very effective when considering that, in

the same study, KR (which is also seen as an effective countermeasure) resulted in only a 15%

reduction in accuracy over the same time period.

Use of cueing also affects participants' mental states. Participants who were cued not only

performed better, but they also reported experiencing only half as much mental workload as

presented in Figure 12 (Hitchcock et al., 1999; Kamzanova, Kustubayeva, & Matthews, 2014)

and marginally less boredom (Hitchcock et al., 1999). Numerous experiments have also shown

that valid or more reliable cueing facilitates faster reaction times (e.g., Rai & Singh, 2009;

Kamzanova et al., 2014).
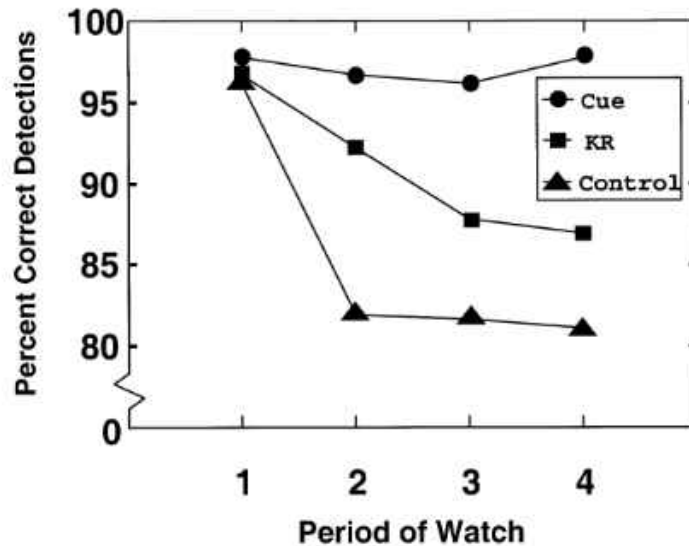
Figure 11. Mean percentages of correct detections of both types of mitigation techniques (cueing, KR) relative to a control group. Taken from Hitchcock et al. (1999). Reprinted with permission.
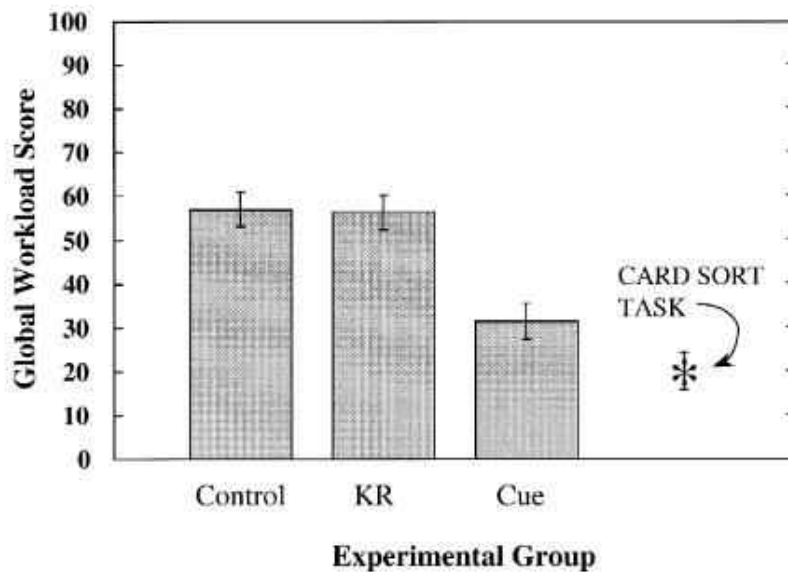
Figure 12. Global perceived workload scores for a simulated air traffic control task based on type of mitigation technique (cueing vs. KR) relative to a control group, as well as an unrelated card-sort task. Taken from Hitchcock et al. (1999). Reprinted with permission.

Knowledge of Results

Feedback using knowledge of results (KR) entails providing participants with information regarding the performance outcomes of their vigil, usually quantified as the number of correct detections, false alarms, missed targets, or by the speed of response relative to the individual's average or a normative criterion. Supplying individuals with feedback has long been recognized as an effective way not only to train vigilance performance (Hitchcock et al., 1999; Mackworth, 1964; Sipowicz, Ware, & Baker, 1962; Szalma, Hancock, Dember, & Warm, 2006, and see Figure 2-12 above), but also to mitigate increases in response time (McCormack, 1959).

J.F. Mackworth (1964) demonstrated that the best performance occurred when participants were provided with accurate KR as opposed to no KR. Similarly, several studies

have shown that both accurate and false KR are effective means of increasing correct detections (Antonelli & Karas, 1967; Mackworth, 1964; Weidenfeller, Baker, & Ware, 1962). Moreover, KR has been shown to reduce response times to signal detections; however, there was no significant time difference between the groups who received true/accurate KR and those who received false KR (Warm, Epps, & Ferguson, 1974). Such findings therefore suggest that performance gains are not necessarily due to the information provided in the feedback, but rather to the attention the feedback focuses on other elements of the task such as: characteristics of the signal, temporal components of the display (Mackworth, 1964), altering participant's expectancies, or providing alternative motivation (Warm, Epps, & Ferguson, 1974).

In a comprehensive study, Wiener and Attwood (1968) tested the efficacy of both KR and cueing training methods on the transfer of signal detection skills. In their protocol, participants were separated into one of four groups: cueing only, KR only, combined KR and cueing, and a no-feedback control group. Each participant then completed a 48-minute vigilance task, parsed into four 12-minute blocks. In the training phase, participants in the combined cueing and KR group maintained the highest detection rate, between 95-100% detection over the course of the vigil. The cueing group exhibited a consistent detection rate of roughly 90%, and the KR group's detection rate ranged between 65-70% throughout the vigil. The no-feedback control group demonstrated the classic vigilance decrement with an initial detection rate of 70% that deteriorated steadily to 30% by the end of the task.

After one week, the participants returned to the laboratory to complete another vigil. However, this time, no cueing or KR were provided to any of the participants at any time. They were to complete the task with no form of assistance (i.e., a transfer session). The group trained

with KR exclusively achieved the highest detection rate, followed by the combined (KR and cueing) group, followed by the cueing only group, and finally the no-feedback group (and see Figure 13; Wiener & Attwood, 1968).
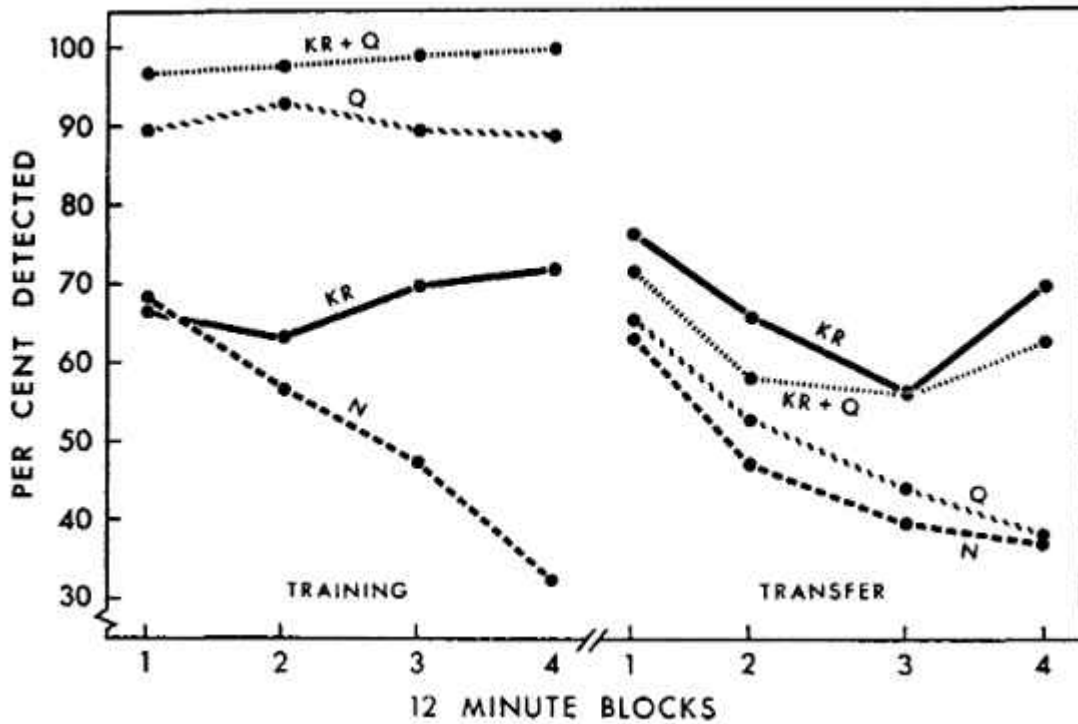
Figure 13. Percentage of correct detections across training groups and periods on watch during both training and transfer stages. Wiener, E.L., & Attwood, D.A. (1968). Training for vigilance: Combined cueing and knowledge of results. *Journal of Applied Psychology, 52* (6), 474-479, published by APA and reprinted with permission.

The format by which KR is presented can also play a crucial role in its effect on performance. Szalma and colleagues (2006) found that KR that informed participants about their correct detections as well as their errors, or composite KR (which provides feedback concerning correct detections, false alarms, and missed critical events) serves to enhance individuals' perceptual sensitivity to signal presence. However, KR that reported either exclusively on false

alarms or solely on misses had no significant effect on signal detection (Szalma, Hancock, Dember, & Warm, 2006).

It is important, however, to point out that performance feedback and neurofeedback are distinct. As previously discussed, KR is a presentation of information regarding performance outcomes on each trial, while neurofeedback constitutes a presentation of task-relevant measures of physiological state. The following section addresses the nature of neurofeedback and its effects on performance and subjective outcomes.

<div align="center">Efficacy of Neurofeedback</div>

Neurofeedback is the process of apprehending one's physiological functioning in order to willfully manipulate it to some purpose. Significant research efforts have supported its relevance in clinical and experimental applications designed to support effective performance. To this end, researchers have employed a number of different physiological systems upon which to base neurofeedback measures, including: skin conductance response (SCR; Gilbert, 1986; Nagai, Golstein, Fenwick, & Trimble, 2004; Savchenko, 1996), rate of respiration (Fried, Fox, & Carlton, 1990; Grossman, Grossman, Schein, Zimlichman, & Gavish, 2001), heart rate variability (Radlo, Steinberg, Singer, Barba, & Melnikov, 2002; Strack, 2003), and most commonly, electroencephalographic cortical activation (Egner & Gruzelier, 2004; Linden, Habib, & Radojevic, 1996; Moore, 2000).

A brief introduction of electroencephalography (EEG), its measures, and correlates to different mental states is now provided. Then, studies using EEG as a neurofeedback training tool for improved performance in cognitive and physical tasks, and its influence over participants' subjective states will be addressed. The focus then shifts to EEG-based

neurofeedback and its specific effects on vigilance performance. Next, the feasibility of establishing functional near-infrared spectroscopy (fNIRS) as a neurofeedback system for enhanced performance is discussed. Finally, the inherent constraints of utilizing psychophysiological indices as metrics for assessing cognition are explored, and justification for the selection of certain physiological measures for the current study is presented.

A Brief Introduction to Electroencephalography: EEG Bands & Associated Mental States

When investigating the effects of neurofeedback on performance, most studies have concentrated on brain waves as assessed by EEG. EEG is a tool psychologists use to record and analyze the electrical activity of regions of the brain. An EEG can record a variety of EEG bands which represent brain waves spanning different frequencies (Neidermeyer, 1999). Of principal concern to this discussion are alpha, beta, and theta waves.

Brain waves cycle at various frequencies that are related to different mental states and behaviors. Most research on EEG and vigilance has focused on three specific frequency ranges: alpha, beta and theta waves. Alpha waves represent cortical activation which cycles at a rate of 8-13 Hz. High alpha frequencies are typically observed under conditions of relaxation, and low alpha frequencies are associated with attention and high mental effort (IFSECN, 1974). Beta waves cycle with a frequency of 13-35 Hz, and higher frequencies in this range are associated with normal waking consciousness and active concentration of the healthy adult (Neidermeyer, 1999). Theta waves have a frequency between 4-7 Hz and higher frequencies have been associated with a state of drowsiness (Neidermeyer, 1999) and the encoding of new information for learning and memory (Klimesch, 1999).

Neurofeedback Training Effects on Cognitive and Physical Performance

Utilizing neurofeedback to enhance alpha power has repeatedly been shown to enhance performance on a variety of cognitive tasks including mental rotation (Hanslmayr, Sauseng, Doppelmayr, Schabus, & Klimesch, 2005; Zoefel, Huster, & Herrmann, 2011) and working memory (Vernon, Egner, Cooper, Compton, Neilands, Sheri, & Gruzelier, 2003). Egner and Gruzelier (2003) have also shown that adoption of a neurofeedback protocol that seeks to increase the theta to alpha activity ratio (which reflects active concentration and sustained attention) improves musical performance (and see Gruzelier, 2009).

Several studies have demonstrated that biofeedback based on heart rate variability has helped to improve both cognitive and physical performance (Raymond, Sajid, Parkinson, & Gruzelier, 2005; Sutarto, Wahab, & Zin, 2010). However, in this work, HRV is an outcome measure; an objective measure of cognitive workload to correlate with the performance outcomes and self-report measures of cognitive and affective states.

The Efficacy of Neurofeedback Training in Vigilance Performance

Research studies investigating which EEG bands are the best predictors of vigilance performance have been equivocal. Several studies advocate that low-frequency alpha is the EEG band most sensitive to vigilance task parameters (Kamzavona et al., 2014). Low alpha frequencies have also been found to precede correctly detected stimuli (Becker-Carus, 1971; Ergenoglu et al., 2004). Belyavin and Wright (1987) found the most accurate discriminator of diminished vigilance performance to be decreased beta activity across all three sections of the beta band (i.e., low beta, beta, and high beta waves). O'Hanlon, Royal, and Beatty (1977) proposed a strong relationship between theta levels and vigilance performance. More

specifically, Daniel (1967) found that theta levels decline prior to failures to detect stimuli; while Makeig and Jung (1996) found that theta increases before the presentation of undetected targets. Others have argued that none of the bands reflect fluctuations in vigilance (Coles & Gale, 1971; Gale, Haslum & Lucas, 1972). Findings are increasingly difficult to interpret as these studies employed a variety of tasks of different modalities and measures of vigilance performance. While EEG-based neurofeedback training has proven effective in a range of contexts despite the equivocal results plaguing its subcomponent indicators (Vernon, 2005), the use of fNIRS may help to provide more conclusive relations between underlying metabolic brain function and accompanying performance measures.

Functional Near-Infrared Spectroscopy as a Neurofeedback Mechanism

In a series of studies, Mihara and colleagues have shown that fNIRS can be used as an effective real-time neurofeedback system to improve cognitive performance in both healthy and clinical populations. Mihara et al. (2013) demonstrated that veridical ('real') fNIRS neurofeedback helped to improve cognitive imagery skills in a group of recovering stroke patients relative to a sham-feedback control condition (i.e., a condition in which the feedback was irrelevant and randomly provided) (see Figure 14). Moreover, the authors established that fNIRS could reliably track blood oxygenation levels in real-time, and that using this index as neurofeedback for healthy adults led to significantly greater cortical activation and more efficacious performance of a cognitive imagery task compared to a sham-feedback group (Mihara et al., 2012). Finally, accurate fNIRS neurofeedback also led to significantly greater performance gains in hand and finger use in patients regaining motor function post-stroke when compared to the sham fNIRS neurofeedback (Mihara et al., 2013).
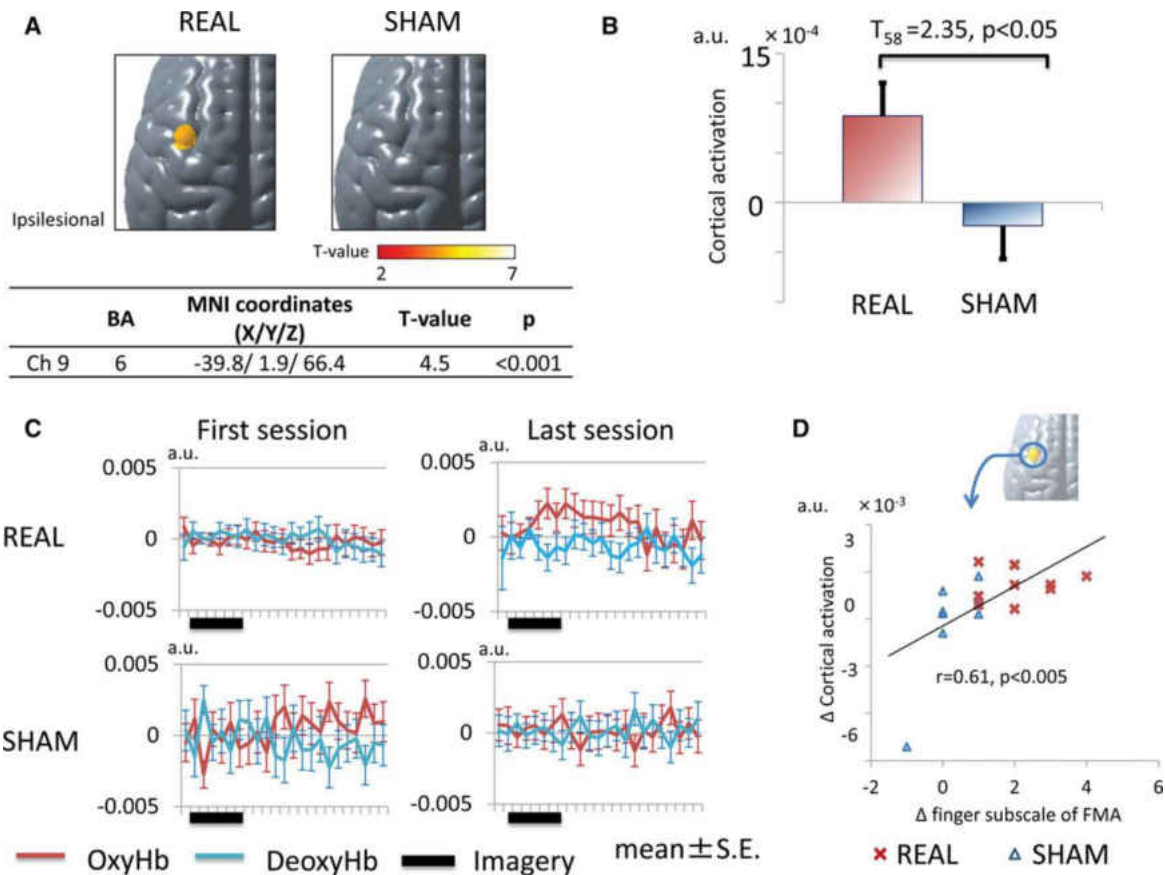
Figure 14. Pictorial representation of the increased cortical activation that accompanied real (as opposed to sham) fNIRS-based neurofeedback in the cognitive imagery task of Mihara et al. (2013). These data were recorded via Channel 9 (Ch 9) on designated Broadmann Area 6 (BA 6) – the Premotor Cortex and Supplementary Motor Area- whose location is specified above via the Montreal Neurological Institute and Hospital (MNI) coordinate system (see part A). The t-value for the statistical comparison between real versus sham feedback conditions is 4.5, which is statistically significant at the $p < 0.001$ level. Reprinted with permission.

Durantin, Gagnon, Trembley and Dehais (2014) found that fNIRS data (generated from oxygenation levels in the prefrontal cortex) can be used as a reliable indicator of mental workload. Similarly, Helton and colleagues (2010) reported that fNIRS data, also collected from the prefrontal cortex of the frontal lobes, could successfully differentiate between levels of mental workload in the context of a vigilance task. Based on these and other previous research

studies, I therefore expect participants to exhibit greater oxygenation (and consequently greater

fNIRS activation) in the prefrontal cortex of the right frontal lobe during a vigilance monitoring

task (Bunce, Izzetoglu, Ayaz, Shewokis, Izzetoglu, Pourrezaei, & Onaral, 2011; Durantin,

Gagnon, Trembley & Dehais, 2014; Helton, Warm, Tripp, Matthews, Parasuraman & Hancock,

2010).

Inherent Constraints of Psychophysiological Measures

It should be noted that drawing conclusions about cognitive states based on

psychophysiological measures should be done with extreme caution. While a number of different

psychophysiological responses have proven reliable indicators of mental constructs such as

emotional response (e.g., Hancock, Hancock & Janelle, 2012) and have been shown to be

reliably sensitive to different levels of task load (e.g., Reinerman-Jones, Matthews, Barber &

Abich, 2014), research suggests that these changes do not seem to reflect the same mental

construct generally identified as 'workload' (Matthews, Reinerman-Jones, Barber & Abich,

2015). Researchers should therefore take the utmost care in selecting appropriate and converging

psychophysiological measures to validly assess cognition, and these should be measured with

and related to measures of performance and self-reports of cognitive state.

To this end, the current studies utilize heart rate variability (via an electrocardiogram) as

an indicator of mental workload. Low heart rate variability has been linked with poorer cognitive

performance and slower response times in sustained attentions tasks (Hansen, Johnsen & Thayer,

2003). Current protocols also use averages of local hemoglobin maxima oxygenation scores (via

functional near-infrared spectroscopy) as an index of mental workload. Averages of local

hemoglobin maxima oxygenation scores were selected as the typical vigilance decrement in

performance over time has been linked with a comparable decline in cerebral bloodflow over the course of the vigil (Warm, Tripp, Matthews & Helton, 2012), as well as increased regional cerebral oxygen saturation (a measure of effective oxygen delivery to a particular region of the brain; Warm et al., 2012).

CHAPTER THREE: METHODOLOGY

Participants

Approximately 100 participants were recruited from the University of Central Florida using the online SONA Research Participation System (SONA) associated with the Department of Psychology. This total was determined by a series of power analyses conducted via G*Power 3.1.9.2 (Faul, Erdfelder, Lang & Buchner, 2007); the parameters for such analyses are illustrated in Table 2. Participants were remunerated with credit in their academic classes via SONA.

Table 2. Parameters for power analyses.

Study	Effect size (f)	α Error Probability	Power (1-β Error Probability)	Number of Measurements	Number of Participants
Psychophysical Equivalency Pilot Study	0.25	0.05	0.80	4	24
1	0.25	0.05	0.80	4	24
2	0.25	0.05	0.80	5	22

Demographic data were collected relating to age, gender, previous exposure to virtual environments, videogame experience, etc. Participants must have reported normal or corrected-to-normal visual acuity. Exclusion from the experiment ensued in the wake of any reports of the following criteria: 1) a history of seizures, 2) currently taking any medication that affects the cardiovascular system, or 3) a history of past or present simulator sickness or discomfort. Such criteria have been identified as means for exclusion as they could bias the integrity of the physiological data (Kennedy, Hettinger & Lilienthal, 1990; Roose et al., 1998). Finally, as

exposure time to virtual environments has been positively related to simulator-induced sickness, participation time was minimized to maintain the validity of the physiological measures (Kennedy, Stanney, & Dunlap, 2000).

<u>Methods and Materials</u>

Psychophysical Equivalency Pilot Study

<u>Software Platforms</u>

All stimuli were developed using Virtual Battlespace 2 (VBS2; Bohemia Interactive, Prague, Czech Republic). The software depicted simulated representations of a typical foot patrol route through an Afghan village in daylight conditions complete with interspersed, ecologically valid critical signals, examples of which are illustrated in Figure 15. Static images and dynamic video clips were derived by excising files from the full-version virtual vigil (and see Figure 16).
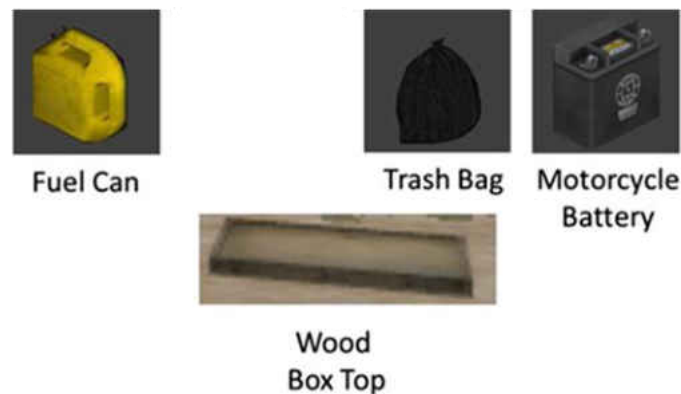
Figure 15. Critical signals for detection in the vigilance protocol. Taken from Szalma, Schmidt, Teo, & Hancock (2014). Modified and reprinted with permission.

Detection performance measures were recorded for off-line analyses using a custom Qualtrics program (Qualtrics, Provo, UT, US). All relevant variables for these analyses were measured, synchronized with each other, and time-locked in relation to stimulus-onset. All

questionnaires were administered electronically using a Qualtrics software platform. All raw data were tabulated and exported for analysis using a standard statistical package (e.g., IBM Statistical Package for the Social Sciences, Software Version 21.0, IBM Corporation, Armonk, NY, US).

Figure 16. A bird's eye view of the simulated route. Participants follow the path that is here demarcated by the blue 'waystations'.

Questionnaires

Dundee Stress State Questionnaire

The Dundee Stress State Questionnaire (DSSQ; Matthews et al., 1999, 2002, 2013) is an assessment tool designed to gauge subjective states in performance contexts. The questionnaire contains subscales to calculate scores for three higher-order factors: Task Engagement, Distress, and Worry. The mood/affect subscale elicits subjective emotional responses to task engagement. Participants' interest in the task and their interest in successfully completing the task are assessed via the motivation subscale. 'Thinking style' evaluates people's beliefs about the task demands

and their feelings of self-efficacy related to its execution; whereas 'thinking content' measures specific intrusive, task-unrelated thoughts. A validated short version of this questionnaire, consisting of 30 items, was used in this dissertation.

NASA Task Load Index

The NASA Task Load Index (NASA-TLX) is a psychometric instrument for quantifying subjective workload (Hart & Staveland, 1988). The questionnaire is comprised of six subscales: three relating to task evaluations (Mental Demand, Temporal Demand, Physical Demand) and three indicating participants' perceptions of their own responses to the imposed task (Effort, Frustration, Performance). Pair-wise comparison analyses were performed to provide weights in the calculation of the global workload scale.

Procedure

Participants began the experiment by reading and signing the informed consent form approved by the University of Central Florida's Institutional Review Board. After assuming the seat in front of the computer, participants completed the electronic versions of the demographic questionnaire and the pre-task DSSQ.

Participants were then asked to complete a two alternative forced choice task (2AFCT) comprised of two, counterbalanced task conditions: one including exclusively still images, the other containing video clips. Each task condition consisted of 20 trials, with each trial comprised of one signal-present stimulus and one signal-absent stimulus shown sequentially. Participants were prompted to indicate which portion of the trial contained the signal (via a button press) after both stimuli were shown. Presentation order of trials (i.e., 10 presenting signal first, 10 presenting non-signal first) was randomized throughout each task condition.

Task difficulty was manipulated by varying the duration of stimulus presentation (i.e., still image exhibition or video clip length). There was a total of three durations: low (stimulus presented for 5 seconds), moderate (stimulus presented for 3 seconds), and high difficulty (stimulus presented for 1 second).

Once responses had been recorded for all trials, participants were asked to complete the NASA-TLX and the DSSQ to assess their subjective experiences while performing the task. The presentation order of these measures was counter-balanced across participants. Finally, participants were debriefed.

Study 1

Study 1 adopted the same software platforms and questionnaires inventoried in the Psychophysical Equivalency Pilot Study. Herein are listed materials and apparatuses unique to Study 1.

Physiological Data Measurement: Heart Rate Variability (HRV)

Electrocardiogram (EKG) data were collected using the BioPac system (Model MP 150) and Acknowledge software 3.9.1 (BioPac Systems Inc., Aero Camino Goleta, CA, US). All cardiac data were collected with a gain of 500 and at a rate of 1,000 Hz. Electrodes were BioPac EL503 disposable, silver-silver chloride electrodes with a 1 centimeter diameter (BioPac Systems Inc., Aero Camino Goleta, CA, US).

Cardiac data were collected via a triangulated electrode configuration. The ground electrode was placed on the tenth rib of the left thorax. Data collection electrodes were placed on the tenth rib of the right thorax and on the left side of the chest (5 centimeters to the left of the jugular notch and inferior to the left clavicle). HRV, defined as the variation in time

(milliseconds) between sequential heartbeats, was used to calculate the cardiac variable of principal interest: HRV difference scores. Baseline HRV was subtracted from phasic HRV activity to generate these change scores.

For several reasons, heart rate variability was selected from among a number of other cardiac biometrics (Berntson, Cacioppo, & Quigley, 1995). Firstly, HRV is sensitive to both increases and decreases in heart rate. Secondly, unlike heart rate that is limited to real-time analysis (seconds or milliseconds), HRV can also be analyzed in cardiac time units (beats). Finally, various studies have found HRV to be predictive of mental workload (Sammer, 1998; Stuiver, de Waard, Brookhuis, Dijksterhuis, Lewis-Evans, & Mulder, 2012) and to be associated with task performance in a simulation-based environment (Lenneman & Backs, 2009).

Procedure

Participants read and signed the informed consent form. Electronic versions of the demographics questionnaire and pre-task DSSQ were then administered. The ground electrode was affixed to the tenth rib of the left thorax. EKG monitors were subsequently positioned on the tenth rib of the right thorax, and on the chest to the left of the jugular notch and beneath the left clavicle on the chest. Physiological baseline data were collected during a two-minute rest period immediately prior to beginning the task. Participants were then shown an image so as to familiarize them with the four potential critical signals to detect during the vigilance task: a car battery, a wooden plank, a trash bag, and a plastic bottle (see Figure 15).

Participants were then instructed to perform two vigilance tasks presented in counterbalanced order: one consisting of static images and the other containing dynamic video clips. Each task condition consisted of 60 trials (10 of which contained critical signals), and each

trial had a duration of 5 seconds per the results of the Pilot Study. Twenty critical signals were

therefore presented at random over the 120 total trials (10 randomized within each condition).

Following the completion of both vigils, participants were asked to complete the DSSQ and the

NASA-TLX. Following the completion of all questionnaires, the EKG electrodes were removed.

Participants were then debriefed, thanked, and any remaining questions regarding their

experience were answered.

Study 2

Study 2 adopted the same physiological data collection system, software platforms, and

questionnaires inventoried in the Psychophysical Equivalency Pilot Study, as well as the

vigilance performance measures specified in Study 1. Herein are listed materials and apparatuses

unique to Study 2.

Physiological Data Measurement: Functional Near-Infrared Spectroscopy (fNIRS)

Changes in the concentration of oxyhemoglobin (oxy-Hb) in cerebral bloodflow will be

measured using a 16-optode continuous wave fNIR Imager 1000 system (fNIR Devices LLC,

Potomac, MD, USA). LED-based sensors were set flush across the participant's forehead and

secured round the head's circumference using a tie-strap. Once activated, the sensors recorded

neural responses in the prefrontal cortex (PFC) via blood oxygen level dependent signals (i.e.,

the BOLD response) in tissue reflectivity. A number of experimental studies have observed a

robust effect of right cerebral hemispheric dominance during vigilance tasks (Warm &

Parasuraman, 2007; Helton et al., 2007; Warm, Matthews, & Parasuraman, 2009), but metabolic

activity of both the left and right hemispheres were recorded and analyzed in this dissertation.

Data were collected via Cognitive Optical Brain Imaging Studio software (Version 1.4.0.25; Ayaz, 2005) and reduced via fNIRSoft software (Version 4.3; Ayaz, 2010).

<u>Procedure</u>

Participants read and sign the IRB's informed consent form. Electronic versions of the demographics questions and the pre-task DSSQ were then administered. The EKG electrodes were applied in the same manner and in the same configuration as detailed in Study 1. Participants were subsequently fitted with the fNIRS strap, and the electrodes placed flush against their foreheads. Raw oxygenation was checked to ensure that levels fell within the 400-4000mV range. If not, adjustments were made as far as possible to the strap and its placement to confirm that non-normal values were not due to a physical barrier (i.e., hair placement). Physiological baseline data were collected during a two-minute rest period before beginning the task. A reminder was then issued to participants to remain as still as possible in their chairs so as not to introduce movement artifacts into the physiological data. A static image (specifically, Figure 15) was then shown to the participants so as to familiarize them with the critical signals to be detected. Participants were told that they would be asked to watch a series of short video clips wherein they were expected to identify one of the four critical signals. If they happened to see one of these signals, they were to respond by clicking on a box labeled 'Signal Detected' located immediately below the video clip. The box was placed below the video clip presentation rather than over it so that the presence of the mouse would not obscure any portion of the visual display. Participants were told that if they did not see any of the critical signals in the video, that they were to refrain from clicking, and that the subsequent clip would begin automatically.

Each participant then undertook a vigilance task comprised of 120 total trials. Each trial comprised the presentation of one five-second video clip. Trials were arranged in 20 total blocks; each block consisting of six trials and five, one-second inter-stimulus intervals. Each block was therefore 35 seconds in duration. In order to accommodate the re-setting of the BOLD response in consideration of the fNIRS data, an interval of 20-30 seconds was placed between each block. To ensure that participants remained vigilant throughout this interval, its duration was randomized (between 20 and 30 seconds) so that the participant was unsure as to the onset of each subsequent block. As a result, the vigil was roughly 21 minutes in total duration. For analyses, this vigil was parsed into five periods on watch, each period comprising four blocks. The randomization of which trial within the block would contain the signal and which signal would be presented in that trial was determined a priori, and all participants experienced the same 'canned' vigil.

Each participant was randomly assigned to one of two groups: a cueing group and a control group. One of the blocks in each period on watch was randomly selected to be the block wherein a tone was presented upon the presentation of the first trial therein. Individuals in the cueing group were told (prior to beginning the task) that should they hear this tone at any time during the vigil, it would be indicative that their physiological signals had declined and that they should therefore re-orient themselves to the task. Control participants were told that the sound of the tone was an indication that the computer system was saving their data. The same tone was presented to both groups at the same volume, and at the same pre-specified junctures during the vigil (i.e., the first trial of Blocks 3, 5, 11, 16, and 18) so that any changes in performance could be attributed to the content of the cue, rather than the presence of an additional auditory stimulus.

Following the completion of all five periods on watch, participants provided responses to electronic versions of the post-task DSSQ and the NASA-TLX which were presented in a randomized order. Finally, the experimenter debriefed and answered any applicable questions for the participants following the administration of these measures.

<u>Data Reduction</u>

Heart Rate Variability

Cardiac data were reduced by measuring the amount of time between subsequent R spikes of the electrocardiogram (and see Figure 17). R spikes typically constitute the greatest change in amplitude accompanying the contractions of the cardiac ventricles (Jevon, 2010). A standard deviation was calculated for the two-minute period of rest prior to task engagement, which served as the baseline value.

In Studies 1 and 2, phasic values were computed by averaging the standard deviations of RR intervals (HRV activity) two to four seconds following stimulus onset of each trial. Data processing was limited to the specified two-second time window as this represents enough time to capture any reaction to the trial, while not being too long so as to average out any observable effect; also, two seconds appears to be the largest average time between subsequent heartbeats in the normal population (Grajales & Nicolaescu, 2006). In Study 1, HRV values of correct detections were averaged over each condition (static and dynamic). In Study 2, HRV values of correct detections were averaged. For each experiment, difference scores were generated by subtracting baseline values from phasic activity. Difference scores constituted the dependent measure for all statistical analyses.

69
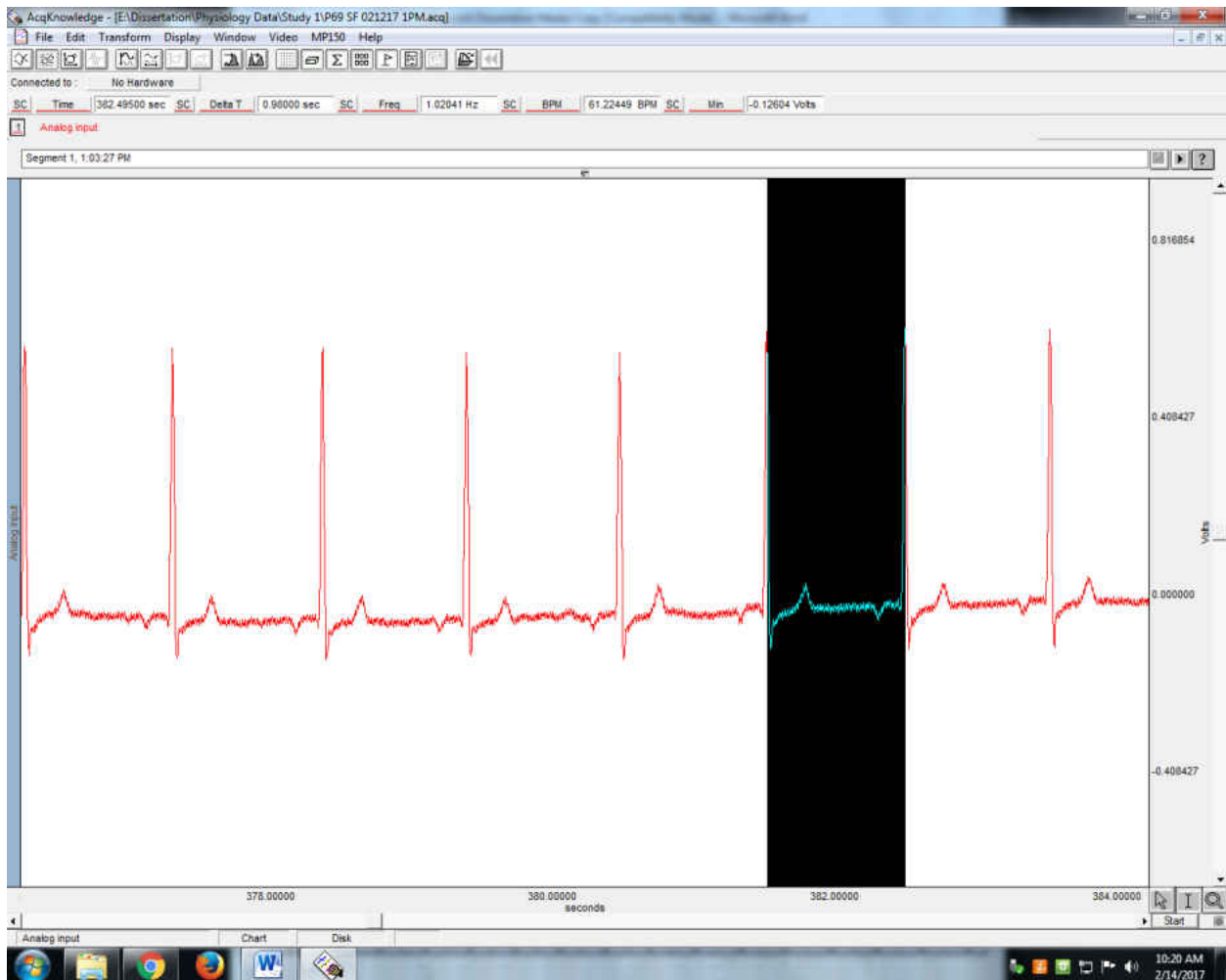
Figure 17. Pictorial representation of a single heart period. Standard deviations will be computed within a set time-window relative to stimulus onset for each study and compared to pre-task baseline values.

Cortical Blood Oxygenation

Optodes are the devices used to collect "back-scatter" from the infrared light emitted by the fNIRS system and subsequently reflected by the different layers of cerebral tissue. Characteristic back-scatter patterns are then able to differentiate between oxygenated and deoxygenated hemoglobin in the blood flowing through said tissues. All optode data were analyzed provided that raw oxygenation levels (i.e., the ratio of oxygenated blood to blood

volume) occupied the range spanning 400-4000 millivolts. Any optodes with signal values falling outside this range were excluded by rejecting that channel. Extraneous physiological noise (i.e., respiration, heartbeats, etc.) was extracted from the data via a low-pass filter. An ambient light filter was also applied to all channels. If, after the application of this filter, the values continued to exceed 4000mV, the channel was excluded from analyses. Extraneous electrically-generated noise (i.e., computer, fNIRS system, etc.) was automatically extracted via an in-built 60 Hz notch filter. Moreover, per Ayaz and colleagues' (2010) suggestion, the data were passed through a Motion Artifact Rejection (SMAR) filter so as to eliminate any movement artifacts caused by excessive head movements. The refined light intensity data were then used to calculate oxygenation. The raw oxygenation data were subjected to another low-pass filter, and detrending was applied to expel drifts in the signal. The performance blocks were defined in relation to the manual markers that indicated the beginning of each block. The local hemoglobin maximum value recorded by each optode and for each block was then identified, and averages of these maxima values computed according to condition, the early (first ten trials) or late (last ten trials) position of the block within the vigil, and for each of the five periods on watch.

Psychophysical Equivalency Pilot Study: Detection Performance

A correct detection entails a participant accurately identifying which stimulus was presented in a given trial contained a signal by clicking on the appropriate option with the mouse after both clips and/or images were shown. The number of correct detections was tabulated by the software, and this value was used for all statistical analyses.

Studies 1 and 2: Vigilance Performance

For Studies 1 and 2, the software platform recorded and indicated participants' correct detections, false alarms, and misses relative to the presence of the critical signals. After the participant generated their response (i.e., clicked the appropriate option with the mouse), the software generated a timestamped Microsoft Excel sheet that afforded quantifying the number of correct detections, false alarms, and misses.

Questionnaire Data

In all studies, participants were asked to complete questionnaires before and after the vigil at time junctures specified in the aforementioned procedures. For the DSSQ, pre-task values were subtracted from post-task scores in order to generate the difference scores for analysis. NASA-TLX global workload scores were calculated by taking an average of the appropriately weighted subscale scores.

Statistical Analyses

Psychophysical Equivalency Pilot Study

To determine whether the dynamism of stimulus presentation (i.e., movement-based versus static) affects detection performance, detection performance measures were analyzed via a 2 (STIMULUS TYPE: Still Image vs. Video Clip) X 2 (TASK ORDER: Images First vs. Clips First) X 3 (DURATION: 5 sec, 3 sec, 1 sec) mixed ANOVA with repeated measures on the first and third factors. All questionnaire data were analyzed via a between-subjects (TASK ORDER: Images First vs. Clips First) ANOVA. Any main effects or interactions yielded by such analyses were subjected to the appropriate Tukey's post-hoc tests. Moreover, Greenhouse Geisser

adjusted degrees of freedom will be reported in the cases in which the sphericity assumption was violated. An acceptable probability value of $p < .05$ was assumed for all analyses in all studies.

Study 1

To determine whether the dynamism of stimulus presentation affects detection performance, vigilance performance measures (correct detections) as well as cardiac measures were separately analyzed via a 2 (STIMULUS TYPE: Still Image vs. Video Clip) X 2 (TASK ORDER: Images First vs. Clips First) mixed ANOVA with repeated measures on the first factor. Similarly, all questionnaire data were analyzed via a between-subjects (TASK ORDER: Images First vs. Clips First) ANOVA.

Study 2

Vigilance performance measures, cardiac measures, and oxygenation levels were analyzed using two separate 2 (CUEING CONDITION: Cueing vs. No Cueing) X 5 (Periods on Watch) mixed factorial ANOVAs, with repeated measures on the second factor. All questionnaire data were analyzed via between-subjects (CUEING CONDITION: Cueing vs. No Cueing) ANOVA.

CHAPTER FOUR: RESULTS

Psychophysical Equivalency Pilot Study

Participants

A total of 29 individuals were recruited to participate in this study. One female participant's data were excluded due to equipment failure (the Qualtrics program failed to record her performance data); another female was excused due a pre-existing history of simulator sickness; and, finally, one male participant was excused due to a congenital color vision deficiency. Analyses were therefore conducted on 26 participants (11 males, 15 females) whose ages ranged from 18 to 29 years old with an average age of 21.12 years (SD = 2.75 years).

Detection Performance

Mauchly's test indicated a violation of the sphericity assumption with regards to duration (χ^2 (2) = 8.028, p = .018). Therefore, the degrees of freedom were corrected using the Greenhouse-Geisser estimates of sphericity (ε = .772). There was a significant main effect of duration on detection performance (F (1.545, 38.625) = 18.616, p < .0001, η_p^2 = .437). As illustrated in Figure 18, the hypothesis was supported in that as duration decreased, the number of correct detections significantly declined. Pairwise comparisons show that participants detected significantly more signals in the 5 second duration condition when compared to the 3 second condition (mean difference = 1.115, p < .0001, d = 0.82) and 1 sec duration (mean difference = 1.846, p < .0001, d = 1.31). The difference between the 3 second and 1 second durations was not statistically significant (mean difference = 0.731, p = .096, d = 0.51).

There was also a statistically significant main effect of stimulus type on detection performance (F (1, 24) = 25.333, $p < .0001$, $\eta_p^2 = .514$). Pairwise comparisons indicate that participants made significantly more correct detections when the stimuli were presented statically as opposed to dynamically (mean difference = 1.462, $p < .0001$, d = 0.68). This main effect of stimulus type is shown in Figure 19.

	5 sec	3 sec	1 sec
□ Series1	17.385	16.269	15.538
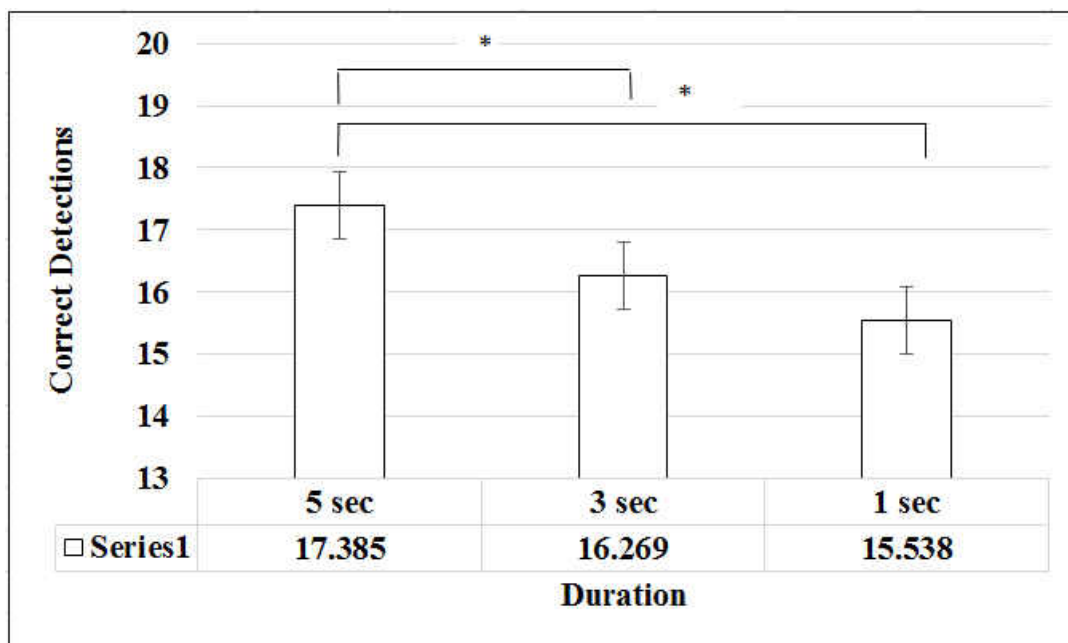
Figure 18. Main effect of duration on detection performance. Errors bars are standard errors. The asterisk denotes a statistically significant difference.

The data additionally revealed a significant stimulus type by duration interaction (F (1.897, 47.425) = 9.390, $p < .0001$, $\eta_p^2 = .281$). As illustrated in Figure 20, the number of correct detections decreased as the duration shortened; however, the marked decline was significantly more drastic in the dynamic as opposed to the static condition.

Figure 19. Main effect of stimulus type on detection performance. Error bars are standard errors. The asterisk denotes a statistically significant difference.
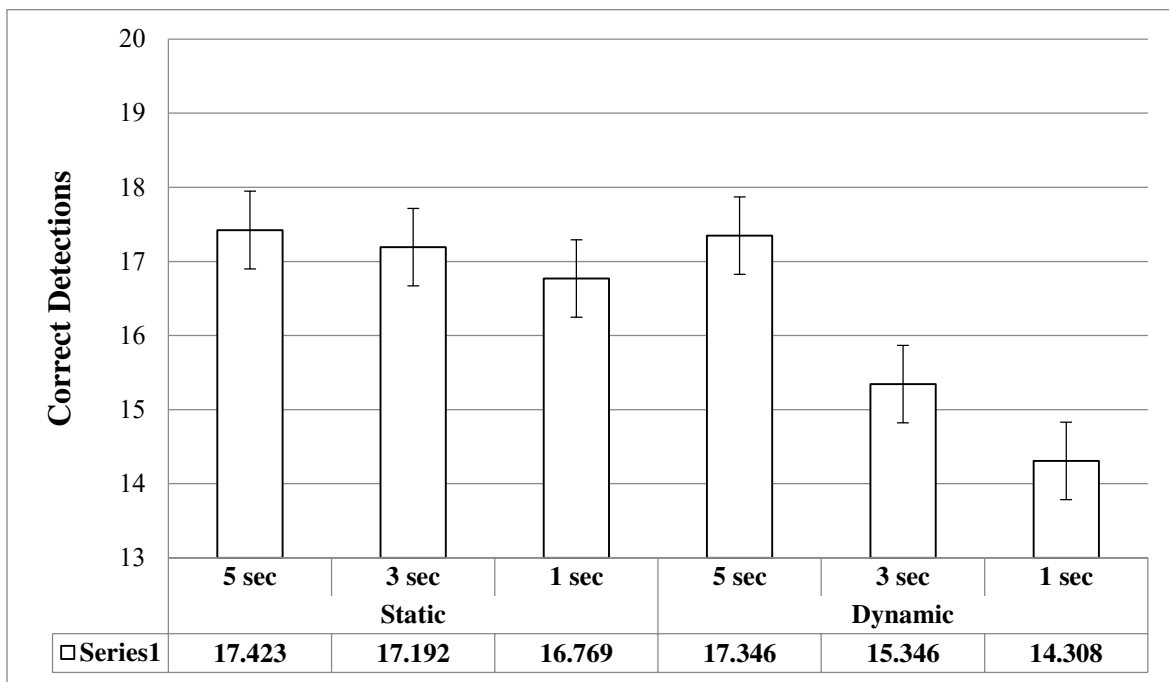
Figure 20. Significant stimulus type by duration interaction. Error bars are standard errors.

Finally, while task order did not exert a significant main effect on detection performance ($F (1, 24) = .002$, $p = .961$), it did prove significant in interacting with stimulus type ($F (1, 24) = 10.674$, $p = .003$, $\eta_p^2 = .308$). Simple effects tests specified that participants who observed static stimuli first correctly detected more signals in the static condition when compared to the dynamic condition ($F (12, 24) = 0.52$). On the other hand, participants who were exposed to the dynamic video clips first also correctly detected more signals when the stimuli were presented statically as opposed to dynamically ($F (12, 24) = 11.48$), as presented in Figure 21.

Series1	Static	Dynamic	Dynamic	Static
	16.667	16.154	15.179	17.59
	Static First		Dynamic First	
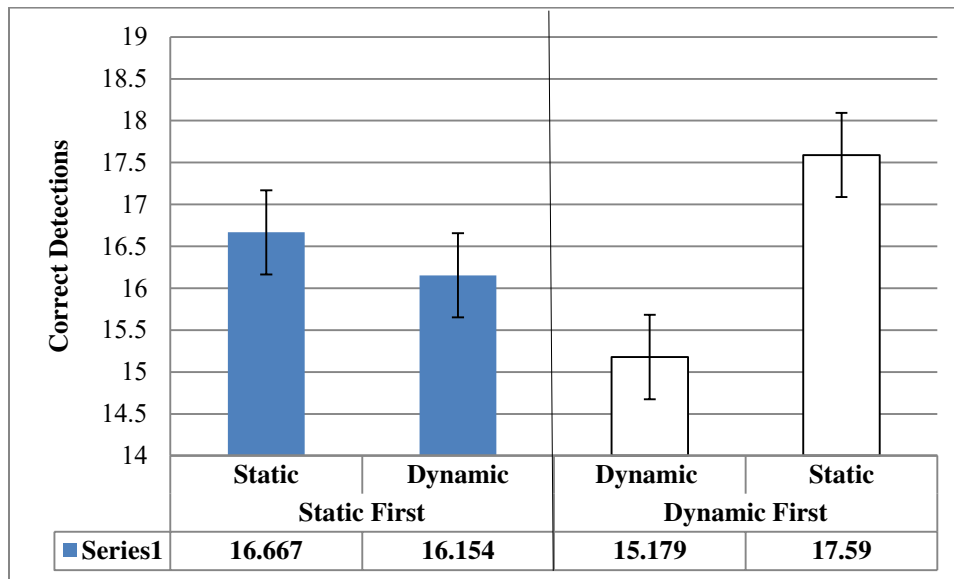
Figure 21. Significant task order by stimulus type interaction. Error bars are standard errors.

Cognitive & Affective States

Dundee Stress State Questionnaire

Univariate analyses conducted on the DSSQ differences (post – pre) scores revealed no statistically significant main effect of task order on either task engagement ($F (1, 24) = 2.012$, $p = .169$) or worry ($F (1, 24) = 3.209$, $p = .086$). There was, however, a statistically significant

main effect of task order on distress (F $(1, 24)$ = 11.172, p = .003, η_p^2 = .318). Pairwise

comparisons show that participants reported greater distress when completing the static condition

first as opposed to the dynamic condition (mean difference = 10.538, p = .003). The hypothesis

was therefore partially supported. Participants did report greater difference scores as measured

by the DSSQ; however, this pattern was only statistically significant on the distress subscale.

	Static First	Dynamic First
□ Series1	12.154	1.615
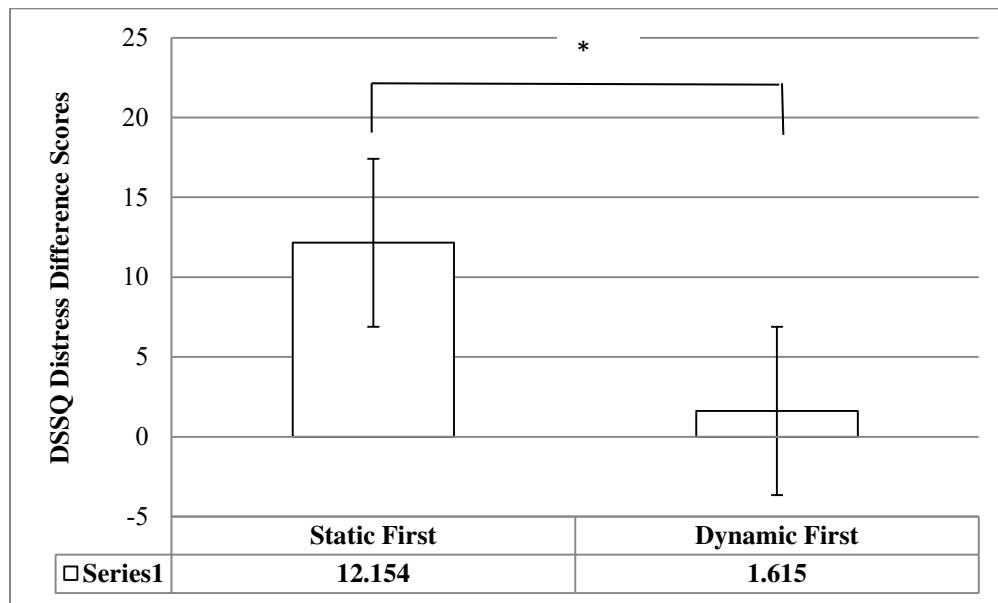
Figure 22. Significant main effect of task order on DSSQ distress difference scores. Error bars
are standard errors. The asterisk denotes a statistically significant difference.

Additional t-tests were performed on the difference scores (post-pre) of the three DSSQ

subscales to determine if there were statistically significant changes in task engagement, distress,

or worry as a result of participating in the task. Two-tailed t-tests revealed that participants

reported experiencing lower task engagement (t(25) = -2.736, p = .011) and greater distress

(t(25) = 3.682, p = .001) due to engagement in the protocol. Worry, however, was not

significantly affected (t(25) = -1.873, p = .073).

Due to a technical error, the pairwise comparisons necessary for computing the weighted subscale averages were not obtained. Therefore, analyses were computed on the unweighted global workload scores, or Raw TLX. It was predicted that participants would report high workload scores. This hypothesis was supported. The Raw TLX average workload score of 46.42 observed in this study is commensurate with the 50th percentile averages of classification (46.00) and cognitive tasks (46.00) generated from a meta-analytic comparison of TLX workload scores derived from over 200 experiments (Grier, 2015). A univariate ANOVA moreover revealed that task order had no significant effect on unweighted global workload as measured by the NASA-TLX ($F_{(1, 24)} = 0.334$, $p = .569$). Based on two-tailed t-test results, the task did impose statistically significant workload on the participants ($t(25) = 14.668$, $p < .001$).

Study 1

Participants

Twenty-six participants were recruited to take part in Study 1 (17 females, 9 males). One male participant was excused due to a pre-existing history of simulator sickness, and a Qualtrics malfunction resulted in the loss of a female participant's performance data preventing its match to her physiological data. As a result, 24 participants (16 females, 8 males) were included in the final analyses for performance. It should be noted that cardiac data could not be analyzed for three participants: the aforementioned female had no recorded performance data to correspond to cardiac output, a malfunction of the time-locking instrument resulted in the inability to synch another female participant's performance data to her physiological data, and one female wore a dress thus precluding the placement of EKG electrodes. Twenty-two participants (13 females, 8

males) were thus included in the analysis of EKG data. The full contingent of participants ranged

in age from 18 to 25 years with an average age of 21.04 years (SD = 2.52 years).

<p align="center">*Vigilance Performance*</p>

<u>Correct Detections</u>

There was a statistically significant main effect of stimulus type on vigilance

performance in terms of correct detections (F (1, 22) = 5.515, p = .028, η_p^2 = .200). As shown in

Figure 23, pairwise comparisons revealed that participants made significantly fewer correct

detections when the stimuli were dynamic as opposed to static (mean difference = 0.741, p =

.028, d = 0.56).

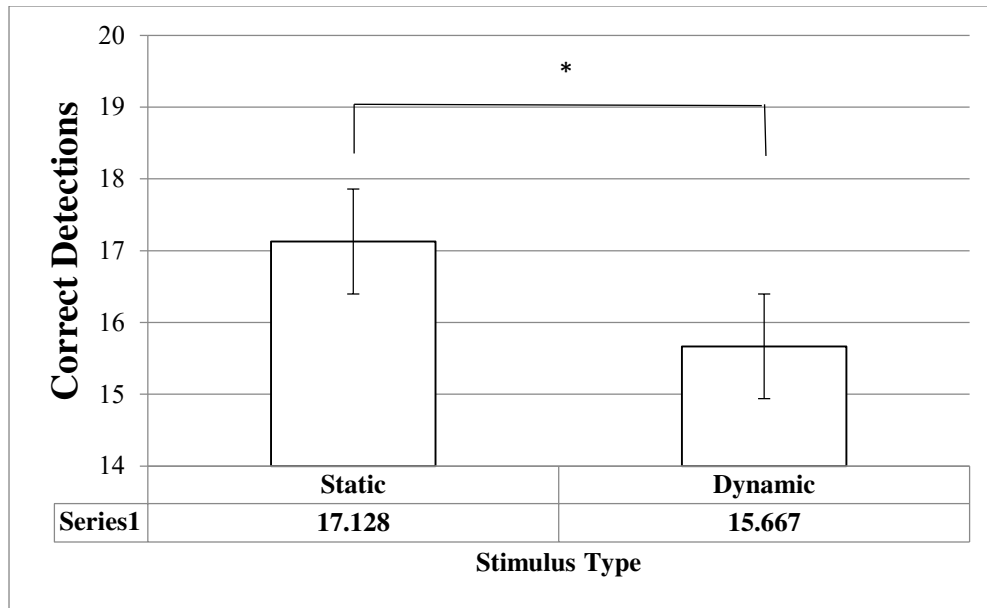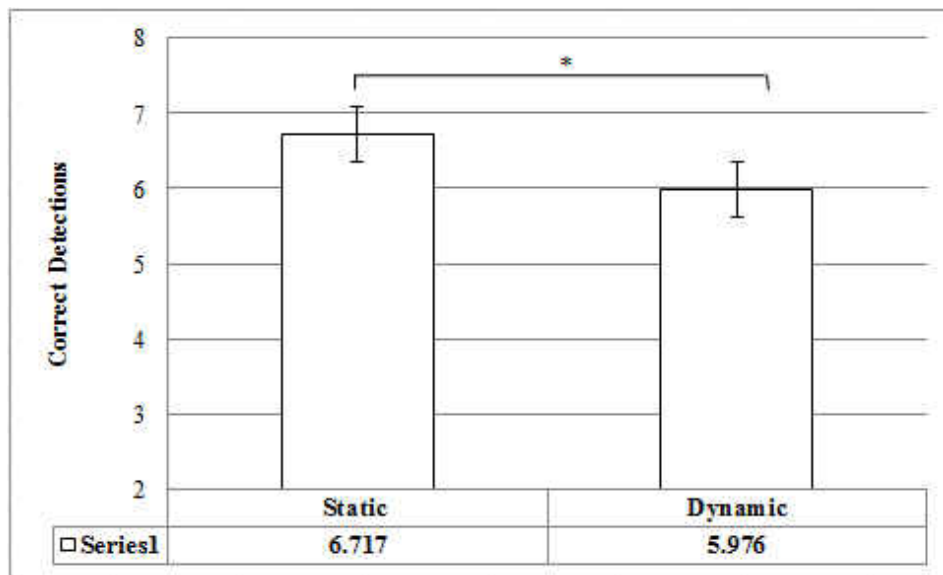Figure 23. Significant main effect of stimulus type on correct detections. Error bars are standard errors. The asterisk denotes a statistically significant difference.

Analyses revealed that task order had neither a main effect (F (1, 22) = 0.491, p = 0.491),

nor an interactive effect (F (1, 22) = 0.110, p = 0.743) on correct detections. The hypothesis was

<p align="center">80</p>

therefore partially supported as there was a significant main effect for stimulus type on vigilance performance, but not in the hypothesized direction. Figure 24 depicts the percentage of correct detections as a function of period on watch.
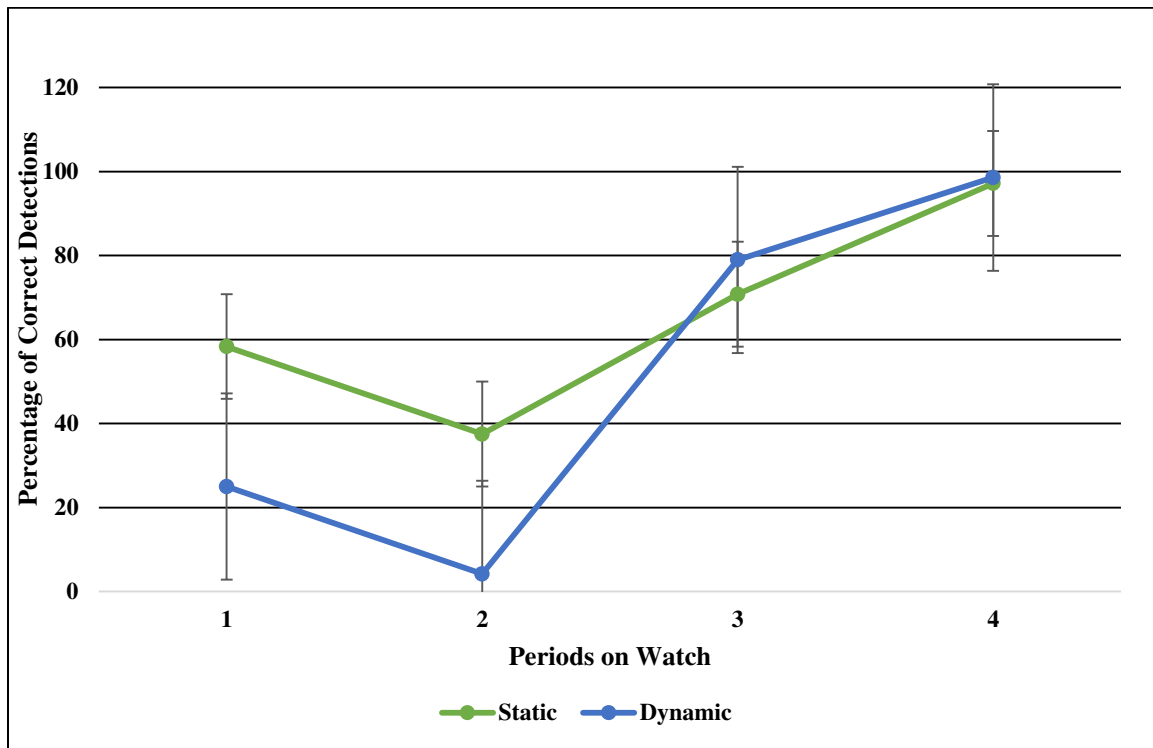
Figure 24. Percentage of correct detections as a function of period on watch. Error bars are standard errors.

False Alarms

There was no main effect for stimulus type on vigilance performance in terms of false alarms, although the trend did approach significance (F (1, 22) = 4.091, p = .055). The hypothesis stipulated that participants would exhibit significantly fewer false alarms in the dynamic versus static condition. As a result, the hypothesis was not supported. Moreover, task order constituted neither a main effect (F (1, 22) = 0.005, p = .944), nor an interactive effect (F

(1, 22) = 4.091, p = .055) on vigilance performance with respect to false alarms. The average

number of false alarms as a function of period on watch is illustrated in Figure 25.
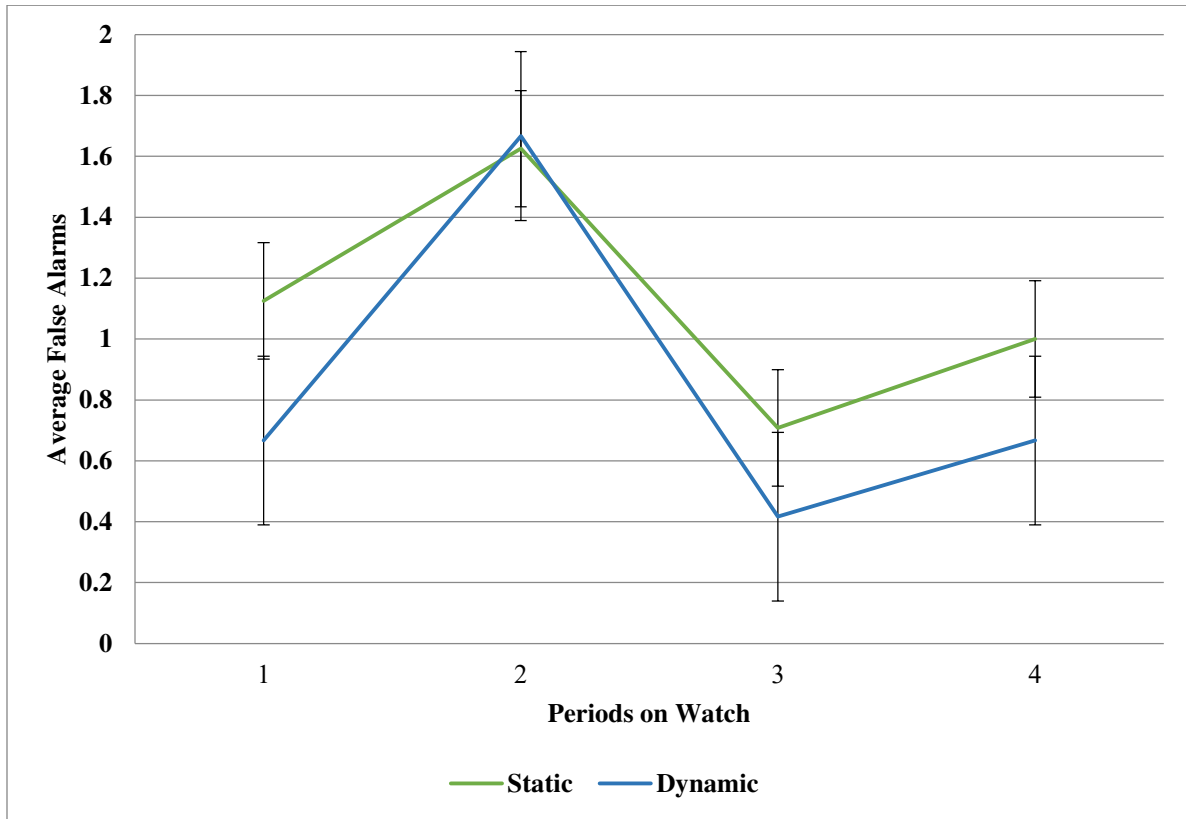
Figure 25. Average false alarms as a function of period on watch. Error bars are standard errors.

Cardiac Activity

Heart rate variability (as measured by standard deviation of all NN intervals (SDNN))

difference scores (phasic – baseline) for all trials in which participants correctly detected the

critical signals were analyzed via a 2 (TASK ORDER: Images First vs. Clips First) X 2

(STIMULUS TYPE: Still Image vs. Video Clip) mixed ANOVA with repeated measures on the

second factor. No main effects for stimulus type (F (1, 20) = .220, p = .644) or task order (F (1,

20) = 2.114, *p* = .162) were observed, nor was the stimulus type by task order interaction

significant (F (1, 20) = 0.779, *p* = .388). The hypothesis was therefore not supported.

However, two-tailed t-tests did reveal that the task imposed significant workload as

measured by heart rate variability. The difference scores were statistically significant for both

static (t (21) = -7.024, *p* < .001) and dynamic (t (21) = -7.306, *p* < .001) conditions. The negative

t-scores in this case indicate that the calculated difference scores (phasic – baseline) were

consistently negative. As a result, individuals' exhibited greater heart rate variability during the

baseline period and less heart rate variability during the vigil, regardless of task condition.

Reduced heart rate variability has been associated with increases in workload and poorer

vigilance performance (Hansen, Johnsen & Thayer, 2003).

<div align="center">*Cognitive and Affective States*</div>

Dundee Stress State Questionnaire

Univariate analyses conducted on the DSSQ difference (post – pre) scores revealed no

statistically significant main effect of task order on any of the subscales: task engagement (F (1,

23) = 0.282 *p* = .600), distress (F (1, 23) = 0.874, *p* = .360), or worry (F (1, 23) = 0.395, *p* =

.536). As a result, the hypothesis which predicted that stimulus type would differentially impact

cognitive and affective states (as measured by the DSSQ) was not supported.

A further series of two-tailed t-tests were conducted to test changes on DSSQ difference

scores as a result of participating in the task. Analyses revealed no stastically significant change

in worry (t (24) = 0.910, *p* = .372). Results did, however, reveal statistically significant changes

in both task engagement (t (24) = -2.316, *p* = .029) and distress (t (24) = 4.151, *p* < .001).

Participants reported significantly lower task engagement and significantly higher distress as a result of undergoing the vigil.

<u>NASA Task Load Index</u>

There was no statistically significant main effect for task order on weighted NASA-TLX global workload averages ($F_{(1, 23)} = 2.795$, $p = .108$). The hypothesis that stimulus type would differentially influence workload was therefore not supported. Nevertheless, a two-tailed t-test revealed that the task itself did impose significant workload on the participants ($t_{(24)} = 20.015$, $p < .001$). No weighted subscale score for Physical Demand, Mental Demand, Temporal Demand, Performance, Effort, or Frustration was significant.

<div align="center"><u>Study 2</u></div>

<div align="center"><i>Participants</i></div>

Twenty-nine participants were recruited to take part in this study. One male participant was excluded due to an inherent color vision deficiency. One female participant suffered a headache due to the weight and tautness of the fNIRS band. She asked as to the duration of the vigil and per IRB directives was told how much time was remaining in the session. As a result, her data were excluded. A total of 27 participants (15 females, 12 males) was therefore included in the final analyses. Participants ranged in age from 18 to 31 years old with an average age of 20.4 years (SD = 2.90 years).

<div align="center"><i>Vigilance Performance</i></div>

<u>Correct Detections</u>

Analyses did not reveal a significant main effect for condition (cueing versus no cueing) on vigilance performance in terms of correct detections ($F_{(1, 25)} = 1.843$, $p = 0.187$).

<div align="center">84</div>

Consequently, the hypothesis was not supported. The period on watch by condition interaction was also not significant (F (3.061, 76.523) = 0.080, p = 0.972).

Figure 26. Main effect of period on watch on correct detections. Error bars are standard errors. Asterisks indicated statistically significant differences.

Mauchly's test indicated a violation of the sphericity assumption with regards to period on watch (χ^2 (9) = 20.122, p = .017). Therefore, the degrees of freedom were corrected using the Greenhouse-Geisser estimates of sphericity (ε = .765). There was a statistically significant main effect of period on watch on vigilance performance in terms of correct detections (F (3.061, 76.523) = 9.819, p < .001, η_p^2 = .282) as illustrated in Figure 26.

Pairwise comparisons revealed that there was a statistically significant greater percentage of correct detections in Period 4 relative to Period 1 (mean difference = 24.176, p = 0.001), Period 4 relative to Period 3 (mean difference = 15.797, p = .004), and in Period 5 relative to

Period 1 (mean difference = 25.962, $p < 0.001$). The percentage of correct detections therefore appears to have increased over time.

<u>False Alarms</u>

There was no statistically significant main effect for condition (cueing versus no cueing) on vigilance performance in terms of false alarms ($F_{(1, 25)} = 0.642$, $p = 0.431$). Consequently, the hypothesis was not supported. The period on watch by condition interaction was also not significant ($F_{(3.072, 76.811)} = 0.545$, $p = 0.657$).

Figure 27. Main effect of period on watch on false alarms. Error bars are standard errors. The asterisk denotes a statistically significant difference.

Mauchly's test indicated a violation of the sphericity assumption with regards to period on watch ($\chi^2 (9) = 19.490$, $p = .022$). Therefore, the degrees of freedom were corrected using the

Greenhouse-Geisser estimates of sphericity (ε = .768). There was a statistically significant main effect of period on watch on vigilance performance in terms of false alarms (F (3.072, 76.811) = 3.783, p = .013, η_p^2 = .131). Pairwise comparisons disclosed that there was a significantly higher average number of false alarms in Period 2 relative to Period 5 (mean difference = 1.827, p = 0.024). This main effect is illustrated in Figure 27.

Cortical Blood Oxygenation

Although cortical blood oxygenation was not one of the dependent measures of interest in Study 2, as the cueing manipulation was only nominally based on operator state, the results are nevertheless herein presented. Oxygenation scores (relative to baseline) were analyzed via a series of mixed-model, repeated measures ANOVAs. A 2 (CONDITION: Cueing vs. Control) x 16 (OPTODE: 1-16) repeated measures ANOVA with repeated measures on the second factor revealed no statistically significant main effect for condition on cortical blood oxygenation (F (1, 12) = 1.152, p = .304), no statistically significant main effect for optode (F (15, 180) = 0.978, p = .480), and no statistically significant condition by optode interaction (F (15, 180) = 1.466, p = .122). Cortical blood oxygenation in the prefrontal cortex (PFC) therefore did not significantly differ between the cueing and control groups. There was a statistically significant difference in scores between several optodes, but none of the effects retained their significance following the adjustment for multiple comparisons. Though the effect was not statistically significant, Figure 28 illustrates the topographs representing cortical blood oxygenation in the cueing and control conditions.

To determine the broad effect of time on cortical activation, average oxygenation over the first ten blocks was compared to oxygenation levels averaged over the last ten blocks via a 2

(CONDITION: Cueing vs. Control) x 2 (TIME: Early vs. Late) x 16 (OPTODE: 1-16) repeated measures ANOVA, with repeated measures on the last factor. Analyses revealed no main effects for either condition ($F (1, 12) = 1.042$, $p = .328$), or time ($F (1, 12) = 0.028$, $p = .871$). The time by optode interaction was similarly not statistically significant ($F (1, 12) = 0.132$, $p = .723$). Again, though there were statistically significant differences between optodes, the significance levels did not meet the threshold necessary for statistical significance following multiple comparisons. Cortical activation averaged across participants and conditions during the first half and latter half of the vigil are presented in Figure 29.

Finally, to more specifically investigate the effect of time on task on cortical activation and to more closely associate this physiological measure with performance data, oxygenation scores were analyzed using a 2 (CONDITION: Cueing vs. Control) x 5 (Periods on Watch) x 16 (OPTODE: 1-16) repeated measures ANOVA, with repeated measures on the second and third factors. Results indicated no statistically significant main effect for either condition ($F (1, 8) = 1.774$, $p = 0.220$) or period on watch ($F (4, 5) = 0.859$, $p = 0.546$). The condition by period on watch interaction was likewise not statistically significant ($F (4, 5) = 0.038$, $p = 0.996$). Despite statistically significant between-optode differences, no statistically significant differences were observed following adjustments for multiple comparisons. Cortical oxygenation over the five periods on watch is portrayed in Figure 30.
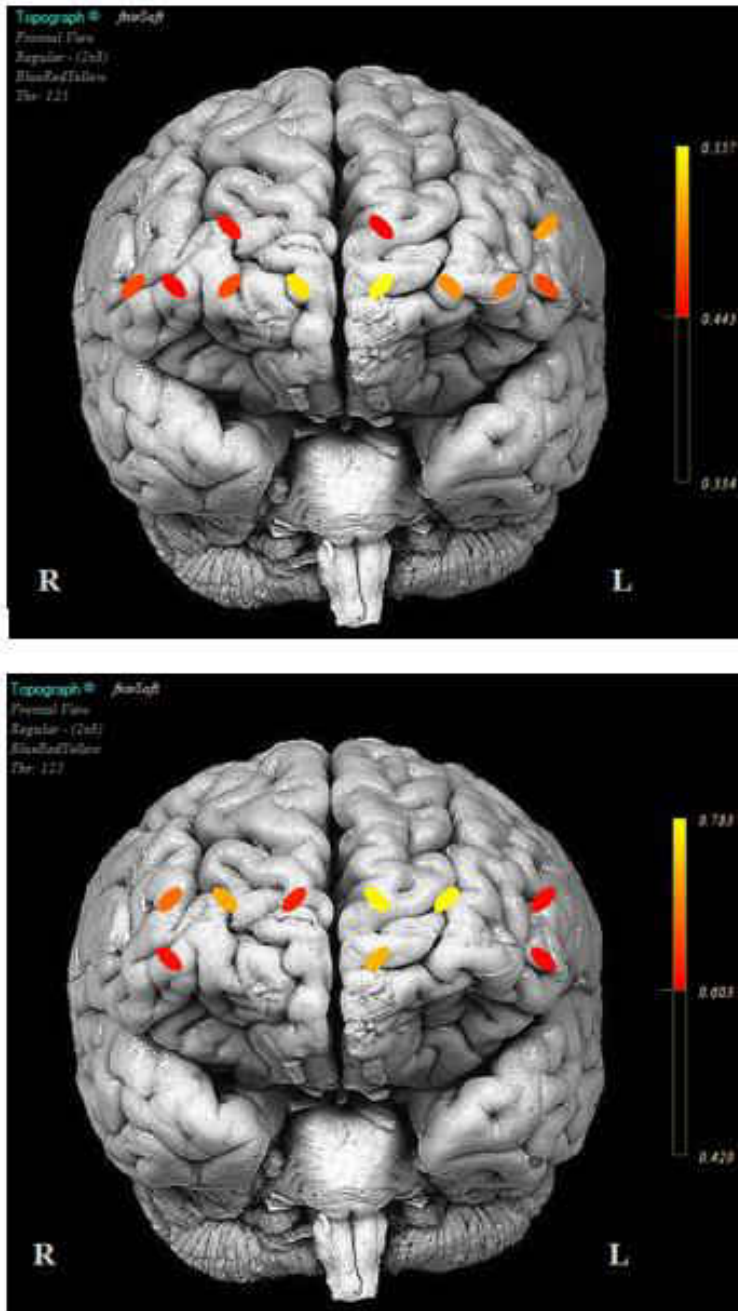
Figure 28. Cortical activation in the cueing (upper image) versus control (lower image) groups.
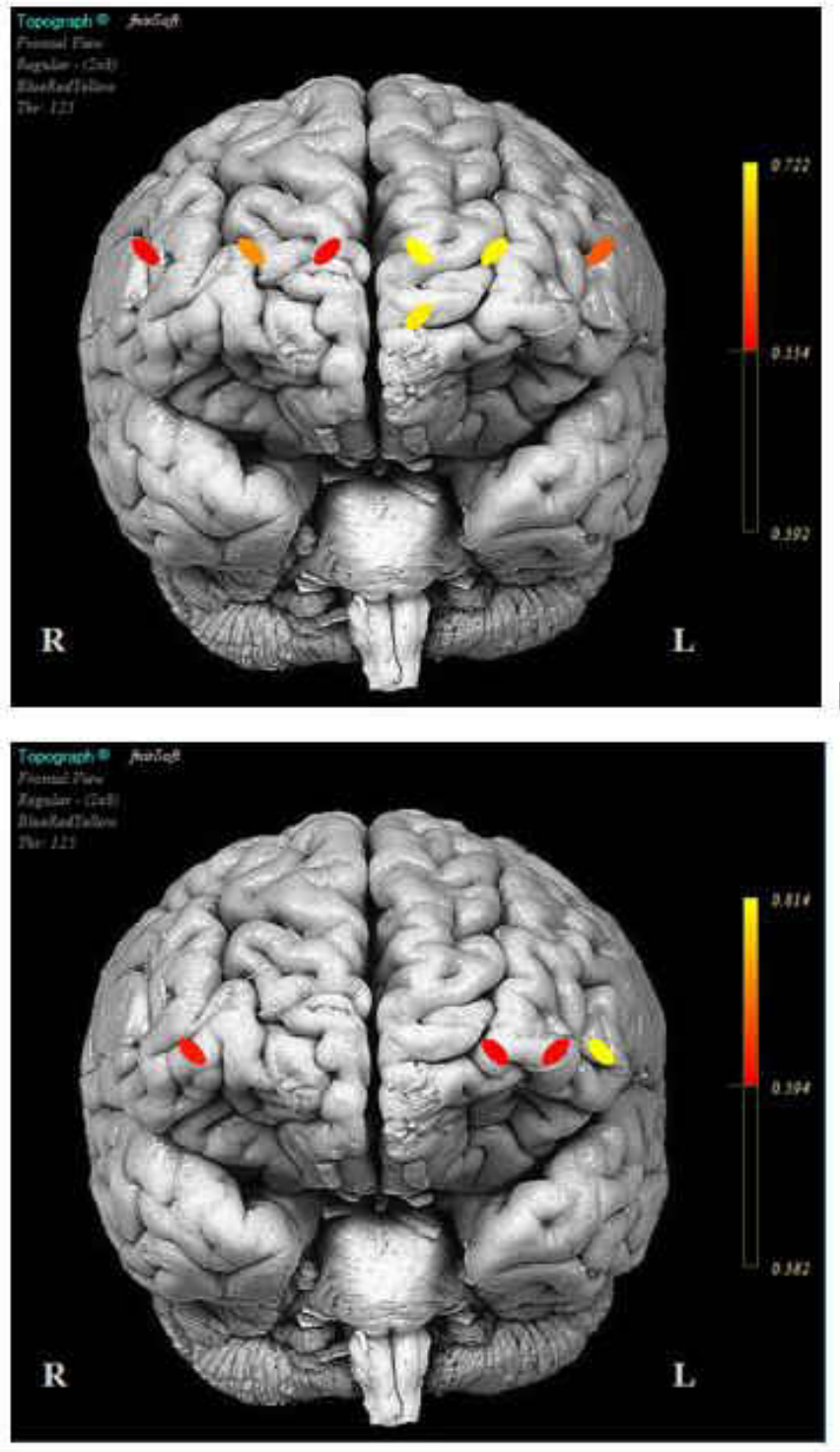
Figure 29. Cortical activation in first half (upper image) versus the latter half (lower image) of the vigil, collapsed across participants and conditions.
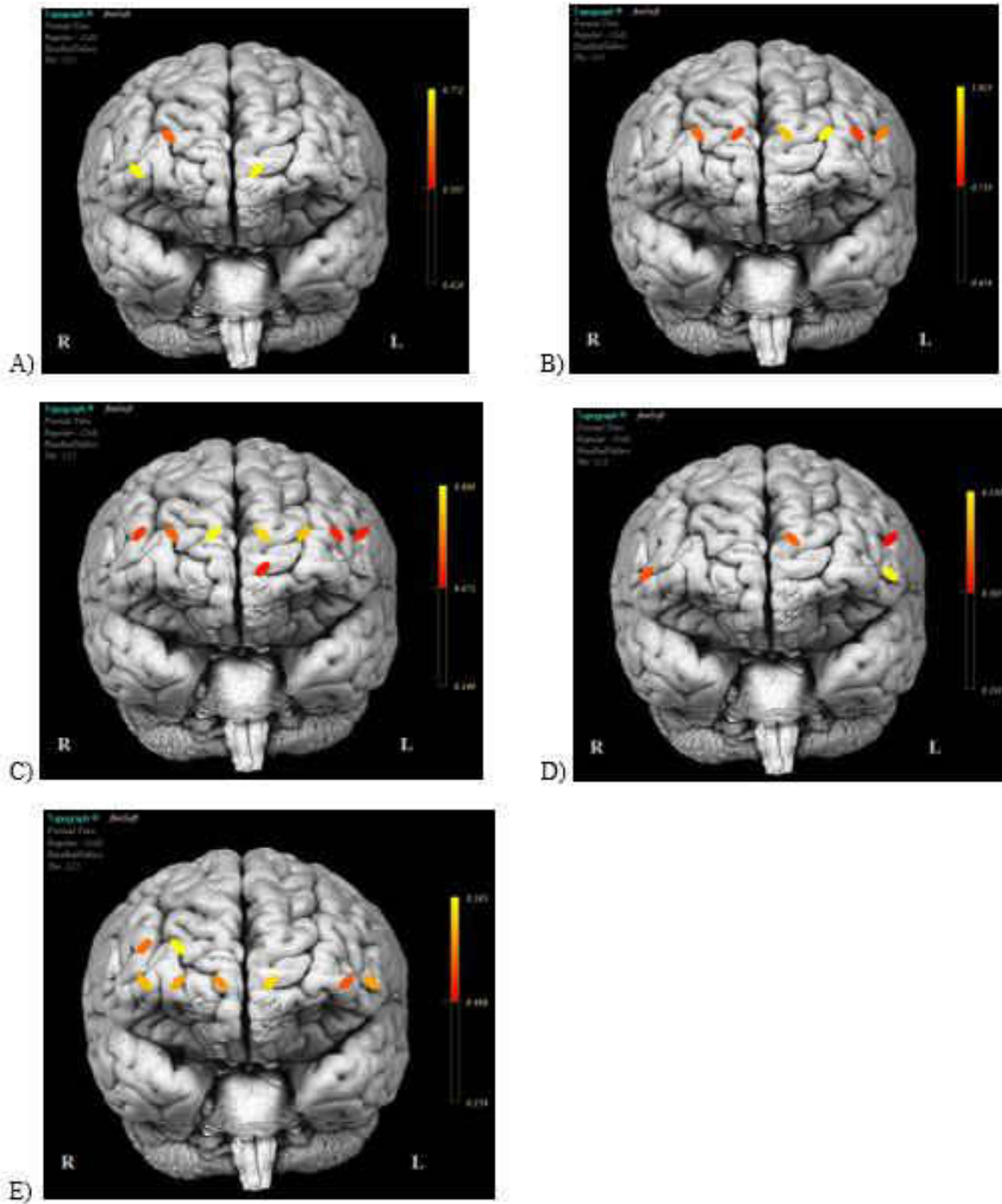
Figure 30. Cortical activation as a function of period on watch. Images A-E correspond sequentially to Periods 1-5.

Cardiac Activity

Heart Rate Variability Difference Scores

Heart rate variability difference scores (phasic – baseline) for all trials in which participants correctly detected the critical signals were analyzed via a 2 (CONDITION: Cueing vs. Control) X 5 (PERIODS ON WATCH) mixed ANOVA with repeated measures on the second factor. Analyses revealed no main effect for condition on heart rate variability difference scores (F (1, 23) = 1.290, p = 0.268). Similarly, there was no statistically significant main effect for period on watch (F (4, 20) = 0.960, p = 0.451) on HRV difference scores, nor was the condition by period on watch interaction statistically significant (F (4, 20) = 0.682, p = 0.613). The hypothesis that cued participants would exhibit statistically significantly smaller HRV difference scores relative to the control group was therefore not supported.

Heart Rate Variability

Phasic heart rate variability for all trials in which participants correctly detected the critical signals were analyzed via a 2 (CONDITION: Cueing vs. Control) X 5 (PERIODS ON WATCH) mixed ANOVA with repeated measures on the second factor. Analyses revealed no main effect for condition on heart rate variability (F (1, 23) = 0.028, p = 0.868).

Mauchly's test indicated a violation of the sphericity assumption with regards to period on watch (χ^2 (9) = 24.420, p = .004). Therefore, the degrees of freedom were corrected using the Greenhouse-Geisser estimates of sphericity (ε = .630). There was a significant main effect of period on watch on HRV (F (2.522, 57.995) = 5.460, p = .004, η_p^2 = .192). Pairwise comparisons disclosed that there was a significantly higher HRV in Period 1 relative to Period 5

(mean difference = 0.050, p = 0.006), and in Period 4 relative to Period 5 (mean difference = 0.027, p = 0.022). This main effect is illustrated in Figure 31.
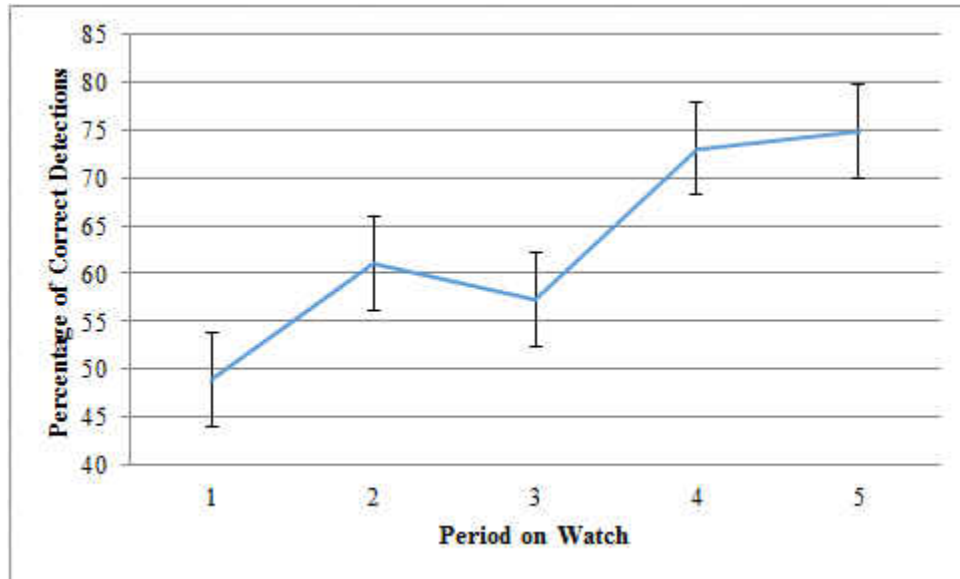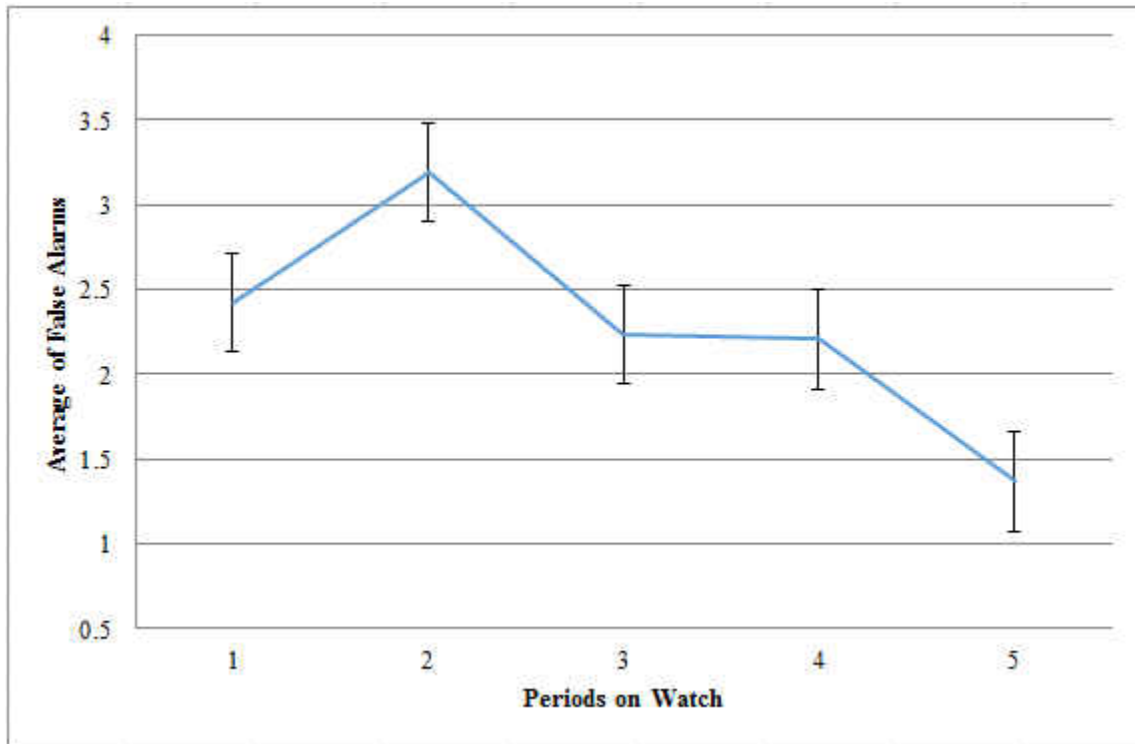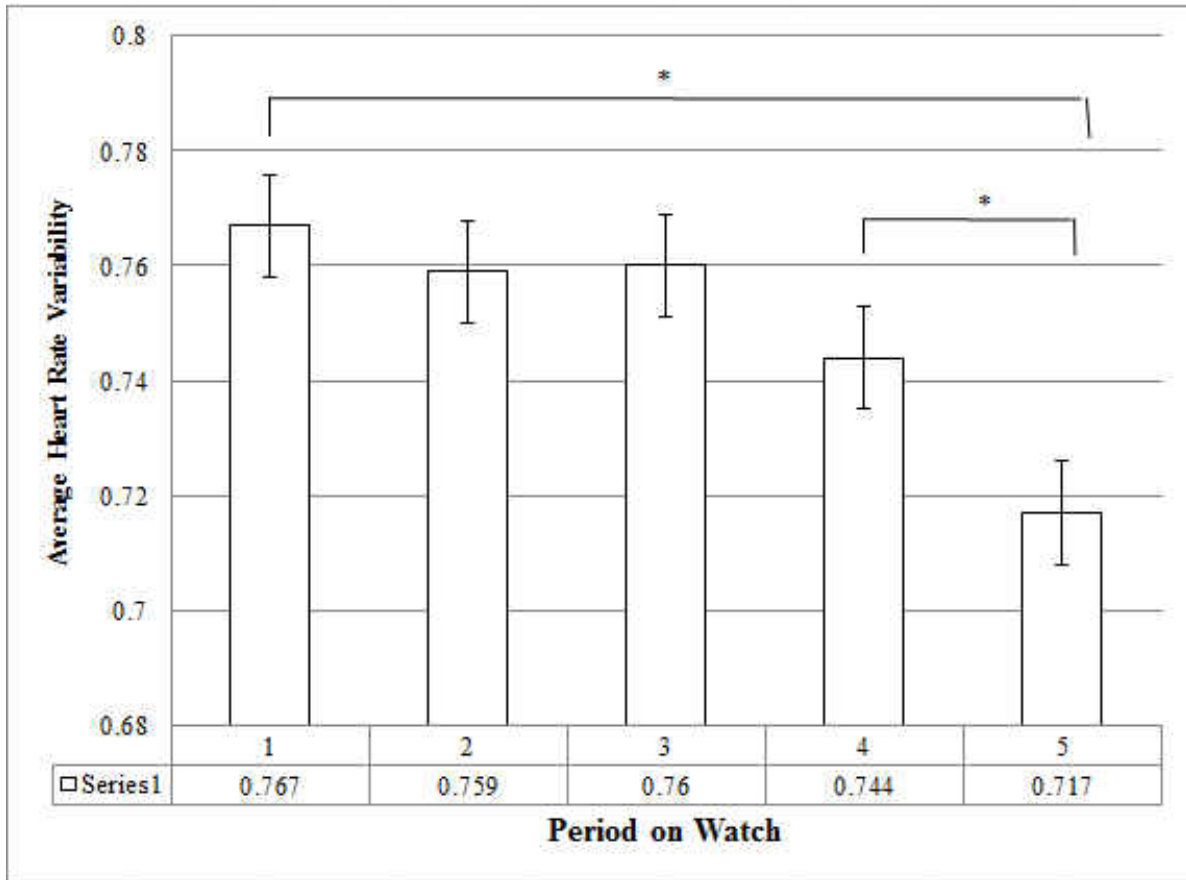

Figure 31. Main effect of period on watch on heart rate variability. Error bars are standard errors. Asterisks denote statistically significant differences.

Analyses also specified that the period on watch by condition interaction was also statistically significant (F (2.522, 57.995) = 3.830, p = .019, η_p^2 = .143) as shown in Figure 32. Both conditions seem to experience a decrease in HRV as a function of time on task. The general linear decline appears to be steeper for the control group relative to the cued group.

	Cued					Control				
	Period 1	Period 2	Period 3	Period 4	Period 5	Period 1	Period 2	Period 3	Period 4	Period 5
□Series1	0.751	0.757	0.735	0.742	0.736	0.783	0.761	0.784	0.745	0.697
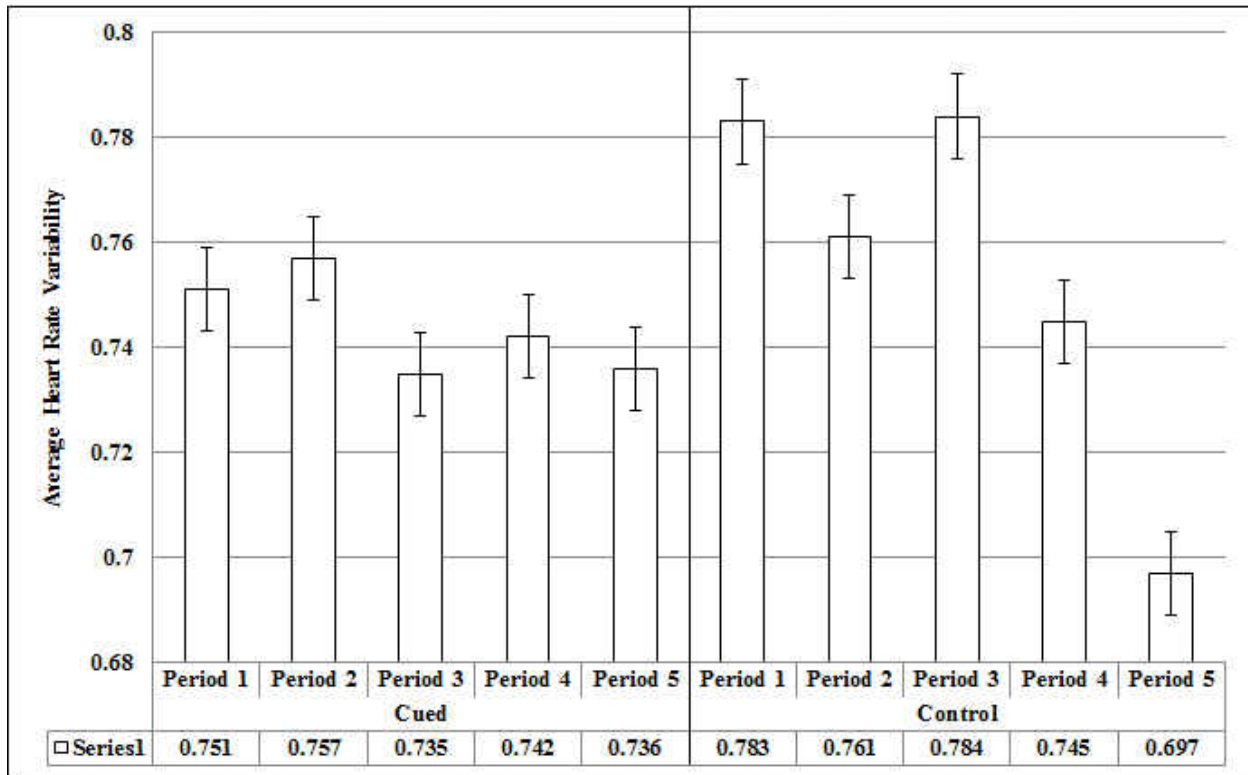
Figure 32. Significant Condition by Period on Watch interaction in heart rate variability. Error bars are standard errors.

Cognitive and Affective States

<u>Dundee Stress State Questionnaire</u>

Univariate analyses conducted on the DSSQ differences (post – pre) scores revealed no statistically significant main effect of condition on any of the subscales: task engagement ($F_{(1, 25)} = 0.398$, $p = .534$), distress ($F_{(1, 25)} = 0.428$, $p = .519$), or worry ($F_{(1, 25)} = 0.671$, $p = .420$). As a result, the hypothesis which predicted that the cueing would differentially impact cognitive and affective states (as measured by the DSSQ) was not supported.

Two-tailed t-tests were conducted to test changes on DSSQ difference scores as a result of participating in the vigil. Analyses revealed no statistically significant change in worry ($t_{(26)} = -0.875$, $p = .390$). Results did, however, reveal statistically significant changes in both task

94

engagement (t (26) = -5.685, *p* < 0.001) and distress (t (26) = 6.452, *p* < .001). Participants reported significantly lower task engagement and significantly higher distress as a result of undergoing the vigil.

NASA Task Load Index

There was no statistically significant main effect for condition on weighted NASA-TLX global workload averages (F (1, 225) = 0.040, *p* = .843). The hypothesis that cueing would differentially influence workload was therefore not supported. A two-tailed t-test did, however, reveal that the vigil imposed workload (t (26) = 22.428, *p* < .001). None of the weighted subscale scores (Physical Demand, Mental Demand, Temporal Demand, Performance, Effort, or Frustration) was significant.

CHAPTER FIVE: DISCUSSION

For almost seventy years, empirical research has studied factors that contribute to the vigilance decrement function (Mackworth, 1948; Scerbo, 1998a), such as event rate (Parasuraman, 1979), signal discriminability and task type (Parasuraman & Mouloua, 1987). When characteristics of these elements combine with inherent constraints in information processing capabilities, failures in vigilance often occur. Given that these failures frequently transpire in performance domains that entail significant risk to human health and well-being, the consequences of such lapses in vigilance are dire. Consequently, scientists have sought to establish, validate, and implement effective countermeasures to such declines in order to maintain and improve vigilance performance. The two most successful countermeasures to date have been knowledge of results (providing post hoc feedback concerning performance) and cueing (presenting reliable prompts regarding single onset probability) (Wiener & Attwood, 1968).

While experimental studies have identified certain influences underpinning the decrement, and have tested the cogency of different methods of contravening the maladaptive performance trend, two important considerations that have not been addressed are stimulus type and cue type. This dissertation therefore focused on stimulus type (static versus dynamic stimulus presentation) and cue type (cues based nominally on operator state rather than environmental factors), and their potential effects on vigilance performance. A greater understanding of these constructs is necessary as they entail considerable consequences regarding the representativeness of experimental protocols designed to reproduce real-world task demands in the laboratory, and the conclusions of research based upon such simulations.

Moreover, cueing based on an operator's physical state could prove to be a more effectual countermeasure for the vigilance decrement as it can be more accurately assessed in performance domains where information relating to signal onset probability is difficult to assess and predict.

The current dissertation therefore sought to address these issues by 1) testing participants in a vigilance protocol comprised of both static and dynamic stimuli and evaluating their performance, physiological responses, and subjective reports of workload and stress; and 2) assessing performance outcomes, physiological functioning, and subjective reports of workload and stress while providing cues nominally based on operator state rather than environmental indicators. Novel findings from this work indicate that stimulus type does have an effect on vigilance performance, and subjective reports suggest that a vigil comprised of dynamically presented stimuli produce the same stress profile as vigilance protocols that utilize static stimuli. Such findings are of particular importance to the design of future experimental tasks as performance was affected by this factor, yet physiological indices and subjective reports remained insensitive. Physiological changes (specifically in cardiac activity and cortical blood oxygenation) and their relation to vigilance performance are herein presented. The limitations, theoretical implications, and practical applications of the current work, as well as future directions for the development of this line of research are also discussed.

Psychophysical Equivalency

The pilot study sought to ascertain the appropriate task parameters for the experimental protocols of the subsequent studies. With the obtained results, the study succeeded in determining the statistical psychophysical equivalency of the visual stimuli. Participants were capable of correctly detecting critical signals equally well (static mean = 16.923, dynamic mean

= 16.692) under alerted conditions when the stimuli were presented over a longer duration (5 seconds) versus shorter durations (3 seconds and 1 second). The difference between the two averages at 5 seconds also yielded the smallest effect size (0.046) of any of the other comparisons. It should be noted that the two stimuli cannot be considered truly equivalent unless both distributions are Gaussian; however, of the multiple comparisons made between stimulus types and durations and having failed to reject the null hypothesis, the 5 second static and dynamic stimuli were considered equivalent with one another, and were consequently designated as equally detectable. The trials of Study 1, intended to measure vigilance performance, were therefore 5 seconds in duration in both the static and dynamic conditions. Also, as task order was observed to be a statistically significant interactive factor influencing detection performance, the task conditions remained counter-balanced in Study 1.

Results from subjective reports affirmed that the task mental workload and stress on participants. DSSQ subscales (t-test results) indicated that the 2AFCT had much the same stress profile as traditional vigilance protocols: significantly lower task engagement, significantly higher distress, and no significant effect on worry. The 5 second duration was thus considered to be the most effective length of stimulus presentation by both detection performance outcomes and subjective reports. Thus, trial lengths in both Studies 1 and 2 were five seconds in duration.

<u>Vigilance Performance</u>

Typical vigilance performance is characterized by a decline in both correct detections and false alarms as a function of time on watch. In Studies 1 and 2, the pattern of results at times resembled this characteristic trend, but overall did not reflect the hypothesized manifestation of the vigilance performance decrement.

Study 1

The characteristic decline in correct detections is typically driven by either a loss of perceptual sensitivity (d´) to discriminate between signal and non-signal (Craig, 1997; Parasuraman, 1998), or a shift in an operator's decision criterion (β) as to when and when not to respond (Howland, 1958; Smit, Eling, & Coenen, 2004). If the decrease in correct detections is due to a loss of sensitivity, one would expect hits to reduce and false alarms to remain constant or increase; whereas, if the deterioration in correct detections is the result of a change in a participant's tendency to respond, one would expect both fewer correct detections and fewer false alarms (Smit, Eling, & Coenen, 2004). The latter case was predicted for Study 1, as it was hypothesized that participants would exhibit fewer correct detections and fewer false alarms over time on watch, and that this pattern of behavior would be significantly more pronounced in response to the statically presented stimuli.

This hypothesis was only partially supported. Correct detections did steeply decline between the first two periods on watch, which coincides with the original performance decrement (Mackworth, 1948) as well as other empirical studies (Teichner, 1974). However, vigilance performance did not continue to drop with time on task as it did in Mackworth's findings, but rather improved as the vigil continued. Taking into account that correct detections sharply declined during the same period between periods 1 and 2 that false alarms notably increased, it would appear that participants were missing signals due to sensitivity issues or practice effects (Parasuraman, 1979; Teichner, 1974).

That being said, the hypothesis was partially supported in that there was a significant main effect for stimulus type, yet in the opposite direction as was hypothesized. Performance

outcomes indicated that participants made significantly fewer correct detections in response to dynamic as opposed to static stimuli. Koelega, Brinkman, Zwep, and Verbaten (1990) investigated the effect of static versus dynamic stimuli on vigilance performance and found a non-significant trend for stimulus type on correct detections with a higher number of correct detections for static as opposed to dynamic signals. These findings are in keeping with the results of the present dissertation. However, the results of the Koelega study should be interpreted with great caution as the authors themselves call into question the 'dynamic' nature of the stimuli they used.

Koelega and colleagues (1990) used flashing lights as their stimuli. A rectangle would appear on the computer screen for 0.7 seconds to constitute a trial. In the static condition, participants were asked to respond when the observed rectangle was 1/6th the brightness of the non-signal rectangles. In the dynamic condition, the same size rectangle was presented on screen for the same length of time as during the static condition (0.7 seconds). This timeframe was then equally divided into three segments. During the first portion (0.23 seconds), the lowest third of the rectangle would flash off and on again. The middle third of the rectangle would then flash off and on during the second segment (0.23 seconds). During the final time period, the top-most part of the rectangle would flash off and on again, leaving the participant with the perception of stepwise, upward motion. Each trial therefore exclusively comprised a signal or a non-signal, whereas the current dissertation allowed for signal and non-signal stimuli to be presented simultaneously. Furthermore, as the authors say, their operationalization of 'dynamic' stimuli required little to no scanning on the participant's behalf to identify elements in different positions of a large and complex display, and offers little to no positional uncertainty of signal

presentation; both of which are prevalent in real-world vigilance tasks. The current dissertation's dynamic stimuli did incorporate these elements by presenting both signals and non-signals via first-person perspective dynamic motion.

Despite not having seen the typical performance decrement, Study 2's vigil was constructed making use of the dynamic video clips that were used in Study 1 for a host of reasons. Firstly, the decrement is not necessarily the function of the length of the vigil, but rather of the task demands that the vigil imposes on the observer (Caggiano & Parasuraman, 2004; Neuchterlein, Parasuraman, & Jiang, 1983; Smit, Eling & Coenen, 2004). Second, therefore, the statistically significant main effect of stimulus type on both detection (Pilot Study) and vigilance performance (Study 1) that indicated dynamic clips led to poorer performance outcomes was a strong recommendation for utilizing the clips. Third, the dynamic video clips constituted relatively high spatial processing on behalf of the participant (Caggiano & Parasuraman, 2004) as not only which trial within the block would contain a signal, but also target selection, target position, and target orientation within each trial was randomized. Fourthly and finally, there was a strong indication that those resource demands imposed by a vigil comprised of dynamic video clips were powerful enough to provoke a decrement given that the subjective accounts of workload and stress seen in Study 1 were commensurate with the distinctive stress profile of vigilance: significantly lower task engagement, significantly more distress, no change in worry, and a significantly higher global workload score.

Study 2

The characteristic vigilance decrement was not observed in Study 2. Instead, the pattern of results appears to resemble a learning curve with correct detections by and large increasing

and false alarms generally decreasing over time. While previous studies have infrequently reported a marked increase in correct detections during the final period on watch, a phenomenon known as the end spurt effect (Bergum & Lehr, 1963; O'Hanlon, 1965), the pattern of results herein observed does not resemble the characteristic vigilance performance decrement (Mackworth, 1948) as correct detections broadly rose with time on task. These results, again, could be due to insufficient sensitivity to distinguish the critical signals from their surroundings. One critical signal in particular, the fuel can, exemplifies this issue. Based on anecdotal reports from participants, the yellow fuel can was originally very difficult to distinguish from beige sandbags in the virtual environment, which could account for the high number of false alarms early on in the vigil. However, again per participant feedback, once they had been exposed to it clearly once or twice, the fuel can became one of, if not the easiest, target to identify, which could therefore explain the high number of correct detections – particularly in the latter half of Study 1's vigil.

There are a number of explanations as to why the vigilance decrement was not observed in Study 2. Some researchers may say that the length of the vigil was insufficient at 21 minutes' duration. A number of experimental studies have elicited the decrement by employing vigils of significantly greater duration such as 90 minutes (Pattyn, Neyt, Henderickx, & Soetens, 2008; O'Hanlon, 1965), two hours (Mackworth, 1948), or more (Johnson & Merullo, 1996). However, as previously discussed, it is not so much the length of the vigil as it is the task demands it imposes upon the participant that should theoretically drive the decrement. In fact, several studies with sufficiently challenging task demands have reliably observed the decrement function

in a manner of minutes (Neuchterlein, Parasuraman, & Jiang, 1983) or even within a few trials (Jerison, 1963).

Two task characteristics that could therefore have led to the absence of the performance decrement in Study 2 are the event rate/target rate and inadvertent cognitive breaks. There appears to be an inverse relationship between event rate and hit rate, wherein correct detections decrease as the event rate increases (Jerison & Pickett, 1964). Event rate has been widely manipulated in the literature with researchers using 10 events per minute (Valentino, Arruda, & Gold, 1993), 30 events per minute (Arruda, Amoss, Coburn, & McGee, 2007), and 40 events per minute (Gunn, Warm, Nelson, Bolia, Schumsky, & Corcoran, 2005). Studies 1 and 2 used quite low target rates at roughly 1 target per minute, and fairly low event rates (10 and 6 events per minute respectively). Pattyn and colleagues (2008) utilized a similarly low event rate (2 or 3 events per minute) and saw their error rate decrease over time, which corresponds to an increase in correct detections as was observed in Study 2. A lower than normal event and target rate may therefore explain the absence of the vigilance decrement.

Moreover, in consideration of the fNIRS measure, the block design for Study 2 incorporated intervals (with duration of 20-30 seconds) between each block wherein no stimuli were presented in order to allow for participants' BOLD response to return to normal levels. While participants were explicitly told to maintain their level of attention throughout these intervals (as the stimuli could appear at any time), the fact remains that participants could have used these periods of time as cognitive breaks during which their mental resources were replenished. Experiencing short intervals without any tasks demands, or even switching between

tasks at sporadic intervals can effectively avert the performance decrement (Ariga & Lleras, 2011).

<center>Physiological Effects</center>

<center>*Cardiac Activity*</center>

Heart rate variability has long been successfully used as an effective indicator of mental workload (Parasuraman, 2003) and a predictor of failures in vigilance performance (Chua et al., 2012; Li, Jiao, Chen, Yang, Wang, & Qi, 2002). Generally speaking, as cognitive workload increases, there is an accompanying increase in heart rate and a decrease in heart rate variability (Parasuraman, 2003). Cognitive workload and HRV therefore have an inverse relationship. According to the resource theory of vigilance, one would therefore expect HRV to decline over the course of a vigil wherein significant cognitive resources are being expended over long periods of time (Masalonis, Duley & Parasuraman, 1999; Jeroski, Miller, Langhals & Tripp, 2014). For this reason, it was hypothesized that HRV difference scores would be statistically significantly smaller 1) in response to dynamic clips as opposed to the static images, and 2) in the cueing versus control conditions. However, the data did not support either of these hypotheses. HRV difference scores on correct detection trials proved insensitive to the stimulus type and cueing manipulations.

This lack of statistically significant change in HRV difference scores over both vigilance studies may be due to two factors. Firstly, the case may be that neither vigil imposed sufficient task difficulty to prompt cardiac reactivity. The subjective reports of workload and stress attest that participants were experiencing significant workload and distress, but perhaps the task was not stressful enough or either manipulation strong enough in such a way as to be consistently

<center>104</center>

reflected in cardiac measures. After all, both vigils involved relatively low event rates and target rates. Cardiac measures have previously been shown as insensitive to cueing manipulations with such low target rates (Pattyn, Neyt, Henderickx & Soetens, 2008).

Results from Study 2 wherein HRV was also examined (in addition to HRV difference scores) revealed a main effect of time on task. With HRV declining as a function of period on watch, this trend would indicate that participants were working harder as the vigil progressed (and see Figure 28). This finding coincides with the performance data and subjective reports of workload and stress provided by the participants. However, these results do not hold with a previous study that found an increase of correct detections with time on task (as this study did), that was instead accompanied by an increase in inter-beat interval (and therefore a rise in HRV) which was not the case in the present Study 2 (Pattyn, Neyt, Henderickx & Soetens, 2008).

Cortical Blood Oxygenation

The cueing manipulation did not result in a statistically significant main effect or interaction in cortical activation during the course of the vigil. However, the relatively greater cortical activation in the right hemisphere during the final period on watch (see Figure 30) is consistent with participants' high workload as indexed by the other constituent measures: better performance as exhibited by a higher number of correct detections (see Figure 26), lower HRV (see Figure 31), and greater subjective workload (high weighted NASA-TLX global workload scores). Moreover, the lateralization of oxygenation in the right hemisphere during vigilance performance is in keeping with previous research findings (Helton et al., 2007; Helton & Warm, 2008; Helton et al., 2010; De Joux, Russell, & Helton, 2013; Langner & Eickhoff, 2013). The lack of statistically significant frontal cerebral activity as measured by oxygenation as a function

of time on watch during an abbreviated vigilance task has likewise been previously observed (Helton, Ossowski, & Malinen, 2013).

The lack of statistically significant changes in oxygenation in response to the cueing manipulation may also be due to the oxygenation's sensitivity to task type as opposed to task load (Matthews, Reinerman-Jones, Barber & Abich, 2015). Despite increases in subjective workload, Matthews and colleagues (2015) rightfully point out that the physiological measures are unable to account for neurocognitive constructs beyond workload that may be at play including: executive control of the regulation of attention (Langner & Eickhoff, 2013), compensatory control (Hockey, 1997), and emotional regulation (Matthews, 2001; Hancock, Hancock, & Janelle, 2012).

Cognitive and Affective States

Neither stimulus type (Study 1) nor cueing (Study 2) induced statistically significant changes in subjective reports of workload and stress. However, the vigilance tasks of both Studies 1 and 2 did produce the same subjective stress profile as traditional vigilance paradigms. According to DSSQ subscale difference scores, participants reported significantly less task engagement, significantly more distress, and no significant change in worry as a result of participating in the vigil. Such outcomes are consistent with the vigilance literature (Grier et al., 2003; Temple et al., 2000; Szalma et al., 2004; Warm, Matthews, & Finomore, 2008). Moreover, the vigilance tasks impelled high workload on the participants as indexed by statistically significant weighted global workload scores on the NASA Task Load Index. Again, these findings are in keeping with results in the published literature (Warm, Dember & Hancock, 1996; Finomore, Shaw, Warm, Matthews & Boles, 2013; Temple et al., 2000). Though weighted

subscales of the NASA-TLX (Physical Demand, Mental Demand, Temporal Demand, Performance, Effort, and Frustration) remained insensitive to the stimulus type and cueing manipulations.

<div align="center">Workload Association & Dissociation</div>

Workload is a multidimensional construct (Matthews, Reinerman-Jones, Wohleber, Lin, Mercado & Abich, 2015). Though many objective and subjective factors have reliably influenced 'workload', these elements are only weakly correlated with one another (Matthews et al., 2015). Dissociations then between performance and objective (physiological) and subjective measures, as were observed in these studies, are not uncommon.

According to Yeh and Wickens (1988), such dissociations generally occur as a result of three scenarios: "when greater resources are invested to improve performance of a resource-limited task; when demands on working memory are increased by time-sharing between concurrent tasks or between display elements; and when performance is sensitive to resource competition and subjective measures are more sensitive to total investment" (pp. 111).

In the present vigilance studies, it was observed that performance was improving with resource depletion and increased effort. These findings are therefore best explained by Yeh and Wickens's first scenario. The vigilance tasks of Studies 1 and 2 constitute one of Norman and Bobrow's (1975) resource-limited tasks, given that the increase in information processing resources as indexed by increased cognitive (effort) and physiological resource allocation (phasic heart rate variability) resulted in improved performance. Under these circumstances, dissociations are likely (Yeh & Wickens, 1988).

General Summary

Results from Study 1 indicate that the variable of stimulus type (static versus dynamic stimuli presentation) had an effect on vigilance performance. Participants' detected significantly fewer critical signals when stimuli were displayed dynamically as opposed to statically. These findings constitute the first empirical evidence that the nature of stimulus presentation (specifically, first person perspective dynamic motion) affects vigilance performance, as previous studies found no significant main effect for relative motion (Koelega et al., 1990).

Results from Study 2 provided no empirical support for the hypothesis that cueing nominally based on an operator's physiological state, as opposed to environmental indicators of signal onset probability, would help to improve vigilance performance. The vigil utilizing exclusively dynamic video clips did not yield an observable decrement, and so, no conclusions as to fNIRS' suitability as the cornerstone of a neurofeedback-based cueing system to mitigate the decrement can be decisively drawn from these data. Alternative means of testing this research question are addressed in the forthcoming limitations and directions for future research sections.

Limitations

There were a number of limitations associated with the design and implementation of these vigilance studies. The primary limitation was the exclusion of response time as a dependent measure. The vigilance decrement is not solely characterized by the degeneration of accuracy, but also by accompanying increases in response time (Pattyn, Neyt, Henderickx, & Soetens, 2008). Technical considerations unique to the adoption of such a novel experimental protocol led to the omission of response time as an official dependent measure of interest in the present research. However, given the modified settings of the Qualtrics software that was used to present

the stimuli and collect the relevant performance data, response time data was recorded and will be analyzed in the future.

An additional limitation was the inclusion of the intervals with no stimuli in order to accommodate the resetting of the BOLD response. As previously mentioned, this design aspect may have facilitated the replenishment of cognitive resources thereby hindering the manifestation of the performance decrement, not through the manipulation of the operator-based cues but rather through the cognitive 'breaks' afforded by the lack of overt, visual task demand (Ross, Russell, & Helton, 2014; Neri Oyung, Colletti, Mallis, Tam, & Dinges, 2002). The future directions section will address how this limitation may be effectively overcome in subsequent research efforts.

Another limitation could have been the strength of the cueing manipulation in Study 2. Participants were given verbal instructions as to the meaning of the tone they would hear to indicate either 1) nominal neurofeedback about their physiological level of functioning, or that 2) the computer system was saving their data. Such verbal instructions and the associated tone may not have been a powerful enough manipulation to convince the participants of the validity of the neurofeedback and its usefulness. Again, the proposed method to address this issue will be presented in the directions for future research section.

Finally, a limitation would be the derivation of HRV measures exclusively from those trials in which participants correctly detected the critical signals. Differences in cardiac activity due to stimulus type (Study 1) and cueing (Study 2) may have been missed due to the exclusion of false alarm, miss, and correct rejection trials from analysis. The decision to incorporate data from only correct detection trials was based on time constraints and the promising HRV results

from the supplementary pilot study that revealed a stimulus type by task order interaction approaching significance at $p = .097$ (and see Appendix C).

Theoretical Implications

Findings from these studies present important implications for the vigilance taxonomy. First presented in 1977, Parasuraman and Davies specified discrimination type (successive versus simultaneous), event rate, source complexity, and sensory modality (Warm & Alluisi, 1971), as key factors that influence the vigilance decrement. Several other contributing factors have since been identified including signal duration and signal intensity among others (Davenport, 1968). The results of Study 1 therefore provide empirical evidence for the extension of this theoretical framework to include stimulus type: whether the stimuli of interest are presented statistically or dynamically. The incorporation of stimulus type into the established taxonomy would therefore entail considerable ramifications for the experimental design of protocols created to replicate real-world task demands in the laboratory, particularly for performance domains that utilize dynamic displays (Donald, 2008; Reinerman-Jones, Matthews & Mercado, 2016).

Practical Applications

Vigilance tasks are inherent to a number of performance domains that drastically impact the health and safety of operators as well as the general public. The goal of vigilance research is therefore to identify causes of the decrement that would put human health and well-being at risk and devise methods that would effectively maintain performance efficiency and safety.

This dissertation has sought to lay the methodological groundwork to empirically test the feasibility of incorporating predictive psychophysiological measures into protocols that use

representative, dynamically presented stimuli in an effort to counteract the performance decrement. Findings from this dissertation and the line of research that shall continue from it may be useful in the design and implementation of human-computer support systems designed to alleviate operator stress and workload in order to sustain or improve vigilance performance, thereby safeguarding human health and safety. Adaptive automation systems could monitor operators' physiological state and use the resulting data to predict when computer-based support would be most helpful in counteracting deteriorations in performance which often accompany work conditions that incite overload or underload (Hancock & Parasuraman, 1992; Bunce et al., 2011).

Directions for Future Research

Specific solutions to the aforementioned limitations of the constituent studies are herein presented, as well as proposed future directions for this line of research. Any replication efforts of the studies should seek to address the limitations of the previous protocols. To that end, replication studies should not incorporate the intervals wherein no stimuli were presented. Future efforts would include a canned vigil engineered so that all trials are 5 seconds in duration with a 1 second inter-stimulus interval between each trial, and then manipulate the placement of trials such that there is a minimum of 20-25 seconds between any two trials containing critical signals. The length of the vigil may also be extended in order to increase the event rate and target rate. Coupling these higher event rates and target rates with the successive-discrimination nature of the task should consequently engender the conditions to produce the decrement (Parasuraman, 1979; and see Figure 33).

A more powerful manipulation for nominal neurofeedback cueing could also be adopted. In the current study, participants were given verbal instructions that a tone constituted neural feedback may have been too weak a manipulation to exact any performance differences. Future efforts should therefore provide a display that shows one or both of the participant's cortical oxygenation or HRV output. The ability to see the fluctuations in physiological output may prove a more convincing cue for participants. Moreover, the verbal information provided to the participants specified that the tone indicated a drop in their physiological output, signaling a cue that they should re-orient themselves to the task at hand. Other studies have coupled the cue with pertinent performance outcome information (i.e., a miss is consequently more likely in the next x number of trials or during the next x minutes of time). Perhaps additional instructions enumerating these performance consequences should be coupled with the neurofeedback-based cue, such as 'as your physiological signals have declined, you are now more likely to miss signals in the future'. Given these proposed changes to the experimental structure, modified replication studies should be performed to determine whether the effect of cue type significantly affects vigilance performance.

Continuing this research at the basic science level, in an effort to gain a better understanding of the utility of developing an fNIRS-based neurofeedback cueing system, its effects should be investigated using a more traditional vigilance protocol in which the decrement has already been reliably observed. Parasuraman (1979) clearly illustrated the types of task conditions that have been known to influence the decrement and how faithfully the combination of such factors has elicited an observable decrement (and see Figure 33). One task that incorporates similar task characteristics to the current protocol (successive discrimination, visual

modality) and can therefore be used to investigate the neurofeedback cueing research question

would be the Sustained Attention to Response (or SART) Task (Parasurman, 1979; Robertson,

Manly, Andrade, Baddeley, & Yiend, 1997). An alternative avenue for future work, for those

scientists who object to the titration of task conditions in the laboratory until a decrement appears

(Hancock, 2013), is to incorporate fNIRS into field studies of performance of naturalistic

vigilance tasks (Perrey, Thedon, & Rupp, 2010).
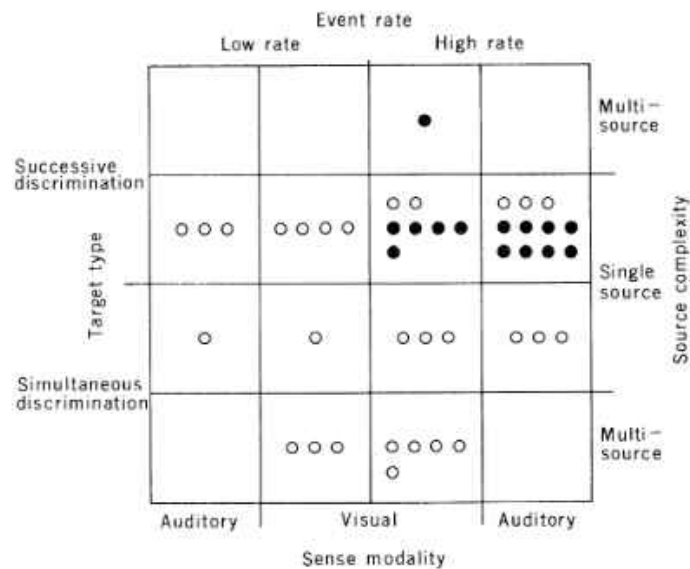
Figure 33. Parasuraman's (1979) classification of vigilance tasks. Black circles denote the conditions under which the vigilance decrement has been reliably observed. White circles represent task conditions under which the decrement has not reliably been seen. Reprinted with permission.

An additional future avenue of research would be to continue to test and develop a new

vigilance protocol involving the continuous (rather than discrete) display of dynamic stimuli.

Such a continuous vigil is arguably more representative of real-world task demands for

performance domains in which 1) spatial and temporal uncertainty of signal presentation is high

and 2) observers are expected to monitor dynamic displays. Following the replication studies necessary to validate such a new vigilance task, fNIRS can then be incorporated to investigate the effects of real-time operator state-based neurofeedback cueing on a continuous, dynamic vigilance task.

<div align="center">Conclusions</div>

The purpose of this dissertation was two-fold: 1) to investigate any effect that static versus dynamic stimulus presentation may have on vigilance performance, and 2) to determine whether cues nominally based on an operator's physiological state (rather than the environment) would prove effective in mitigating the vigilance decrement. As hypothesized, stimulus type did have a significant effect on vigilance performance, with participants detecting significantly fewer critical signals when stimuli were presented dynamically as opposed to statically. These findings suggest that stimulus type is an important factor to consider in vigilance research, as it had a significant effect on performance. However, physiological measures as well as subjective reports of workload and stress were insensitive to it. Researchers should therefore take great care when generalizing results garnered by testing vigilance performance in a protocol using exclusively static stimuli to performance domains that employ dynamic displays.

Contrary to hypothesis, the current work found no evidence that cues based on an individual's physiological state were effective in improving vigilance performance. Such results may be due to the fact that the vigilance decrement was not observed. Further empirical study adopting a task wherein the decrement has already been reliably observed or field studies in relevant performance domains is needed to address this research question.

The current work represents the first empirical evidence that stimulus type exerts a significant influence on vigilance performance, and therefore holds substantial theoretical implications for the vigilance taxonomy. This dissertation also adds the new dimension of using operator-state based cues to the various research efforts attempting to wed psychophysiological measures to the human-computer support systems designed to reinforce and enhance human performance in operational domains central to human health, safety, and security.

APPENDIX A: IRB APPROVAL LETTERS

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Office of Research & Commercialization
12201 Research Parkway, Suite 501
Orlando, Florida 32826-3246
Telephone: 407-823-2901 or 407-882-2276
www.research.ucf.edu/compliance/irb.html

Approval of Human Research

From: **UCF Institutional Review Board #1**
FWA00000351, IRB00001138

To: **Gabriella M. Hancock**

Date: **February 24, 2015**

Dear Researcher:

On 2/24/2015, the IRB approved the following human participant research until 02/23/2016 inclusive:

Type of Review:	UCF Initial Review Submission Form
Project Title:	Psychophysiological Responses in Vigilance Using a Video-Game Based Platform
Investigator:	Gabriella M Hancock
IRB Number:	SBE-15-10996
Funding Agency:	
Grant Title:	
Research ID:	N/A

The scientific merit of the research was considered during the IRB review. The Continuing Review Application must be submitted 30days prior to the expiration date for studies that were previously expedited, and 60 days prior to the expiration date for research that was previously reviewed at a convened meeting. Do not make changes to the study (i.e., protocol, methodology, consent form, personnel, site, etc.) before obtaining IRB approval. A Modification Form **cannot** be used to extend the approval period of a study. All forms may be completed and submitted online at https://iris.research.ucf.edu

If continuing review approval is not granted before the expiration date of 02/23/2016, approval of this research expires on that date. When you have completed your research, please submit a Study Closure request in iRIS so that IRB records will be accurate.

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All data, including signed consent forms if applicable, must be retained and secured per protocol for a minimum of five years (six if HIPAA applies) past the completion of this research. Any links to the identification of participants should be maintained and secured per protocol. Additional requirements may be imposed by your funding agency, your department, or other entities. Access to data is limited to authorized individuals listed as key study personnel.

In the conduct of this research, you are responsible to follow the requirements of the Investigator Manual.

On behalf of Sophia Dziegielewski, Ph.D., L.C.S.W., UCF IRB Chair, this letter is signed by:

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Signature applied by Joanne Muratori on 02/24/2015 04:54:56 PM EST

IRB Manager

Approval of Human Research

From: **UCF Institutional Review Board #1**
              FWA00000351, IRB00001138

To: **Gabriella M. Hancock**

Date: **May 09, 2016**

Dear Researcher:

On 05/09/2016 the IRB approved the following minor modifications to human participant research until 01/21/2017 inclusive:

Type of Review:	IRB Addendum and Modification Request Form
Modification Type:	The studies location has changed from 207B to 113B. A revised protocol has been uploaded in iRIS and both revised Informed Consent documents have been approved for use.
Project Title:	Psychophysiological Responses in Vigilance Using a Video-Game Based Platform
Investigator:	Gabriella M. Hancock
IRB Number:	SBE-15-10996
Funding Agency:	
Grant Title:	
Research ID:	N/A

The scientific merit of the research was considered during the IRB review. The Continuing Review Application must be submitted 30days prior to the expiration date for studies that were previously expedited, and 60 days prior to the expiration date for research that was previously reviewed at a convened meeting. Do not make changes to the study (i.e., protocol, methodology, consent form, personnel, site, etc.) before obtaining IRB approval. A Modification Form **cannot** be used to extend the approval period of a study. All forms may be completed and submitted online at https://iris.research.ucf.edu

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In the conduct of this research, you are responsible to follow the requirements of the Investigator Manual.

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On behalf of Sophia Dziegielewski, Ph.D., L.C.S.W., UCF IRB Chair, this letter is signed by:

Kanielle Chap

IRB Coordinator

Approval of Human Research

From: **UCF Institutional Review Board #1**
FWA00000351, IRB00001138

To: **Gabriella M. Hancock**

Date: **January 22, 2016**

Dear Researcher:

On 01/22/2016, the IRB approved the following human participant research until 01/21/2017 inclusive:

Type of Review:	IRB Continuing Review Application Form
Project Title:	Psychophysiological Responses in Vigilance Using a Video-Game Based Platform
Investigator:	Gabriella M Hancock
IRB Number:	SBE-15-10996
Funding Agency:	
Grant Title:	
Research ID:	N/A

The scientific merit of the research was considered during the IRB review. The Continuing Review Application must be submitted 30days prior to the expiration date for studies that were previously expedited, and 60 days prior to the expiration date for research that was previously reviewed at a convened meeting. Do not make changes to the study (i.e., protocol, methodology, consent form, personnel, site, etc.) before obtaining IRB approval. A Modification Form **cannot** be used to extend the approval period of a study. All forms may be completed and submitted online at https://iris.research.ucf.edu.
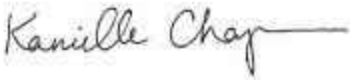
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Use of the approved, stamped consent document(s) is required. The new form supersedes all previous versions, which are now invalid for further use. Only approved investigators (or other approved key study personnel) may solicit consent for research participation. Participants or their representatives must receive a copy of the consent form(s).

All data, including signed consent forms if applicable, must be retained and secured per protocol for a minimum of five years (six if HIPAA applies) past the completion of this research. Any links to the identification of participants should be maintained and secured per protocol. Additional requirements may be imposed by your funding agency, your department, or other entities. Access to data is limited to authorized individuals listed as key study personnel.

In the conduct of this research, you are responsible to follow the requirements of the Investigator Manual.

On behalf of Sophia Dziegielewski, Ph.D., L.C.S.W., UCF IRB Chair, this letter is signed by:

Page 1 of 2

Signature applied by Joanne Muratori on 01/22/2016 12:08:59 PM EST

IRB Manager

Approval of Human Research

From: **UCF Institutional Review Board #1**
FWA00000351, IRB00001138

To: **Gabriella M. Hancock**

Date: **January 13, 2017**

Dear Researcher:

On 01/13/2017 the IRB approved the following human participant research until 01/12/2018 inclusive:

Type of Review:	IRB Continuing Review Application Form
	Expedited Review
Project Title:	Psychophysiological Responses in Vigilance Using a Video-Game Based Platform
Investigator:	Gabriella M. Hancock
IRB Number:	SBE-15-10996
Funding Agency:	
Grant Title:	
Research ID:	N/A

The scientific merit of the research was considered during the IRB review. The Continuing Review Application must be submitted 30days prior to the expiration date for studies that were previously expedited, and 60 days prior to the expiration date for research that was previously reviewed at a convened meeting. Do not make changes to the study (i.e., protocol, methodology, consent form, personnel, site, etc.) before obtaining IRB approval. A Modification Form **cannot** be used to extend the approval period of a study. All forms may be completed and submitted online at https://iris.research.ucf.edu.

If continuing review approval is not granted before the expiration date of 01/12/2018, approval of this research expires on that date. When you have completed your research, please submit a Study Closure request in iRIS so that IRB records will be accurate.

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All data, including signed consent forms if applicable, must be retained and secured per protocol for a minimum of five years (six if HIPAA applies) past the completion of this research. Any links to the identification of participants should be maintained and secured per protocol. Additional requirements may be imposed by your funding agency, your department, or other entities. Access to data is limited to authorized individuals listed as key study personnel.

In the conduct of this research, you are responsible to follow the requirements of the Investigator Manual.

On behalf of Sophia Dziegielewski, Ph.D., L.C.S.W., UCF IRB Chair, this letter is signed by:

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123

Kamille Chap

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From: Experimental Psychology Society <eps@lancaster.ac.uk>
Sent: Tuesday, February 21, 2017 5:43 AM
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Sandra Harris
EPS Administrator
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Department of Psychology
Lancaster University
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Re: Copyright Permission

Hannah G Gotwals <gotwals@mit.edu>

Thu 3/9/2017 10:08 AM

To g.hancock <g.hancock@knights.ucf.edu>;

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Please let me know if you have any questions.

Best regards,
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--

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To: Hannah Gotwals <gotwals@mit.edu>
Subject: Fw: Copyright Permission

Dear Hannah,

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Publication year(s):	1994 - present	**Country of publication:**	United Kingdom of Great
Author/Editor:	International Neuropsychological Society		Britain and Northern Ireland
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APPENDIX C: SUPPLEMENTARY PILOT STUDY

Psychophysical Equivalency Pilot Study Redux: Overall

Considerations

It should be noted that the analysis of cardiac data was completed on 29 of the 30

participants as a malfunction of the Acqknowledge software prevented the heart rate variability

data collection of one female participant. It should also be noted that there is a confound of task

length. Twenty-four participants completed a detection task consisting of 40 total trials, while 6

participants completed a detection task comprised of 80 total trials. The overall analyses are

presented first and the separate analyses based on trial length are presented afterward.

Participants

In accordance with the power analysis conducted prior to the experiment, 33 participants

were recruited to take part in PEPS Redux. One female participant was excluded due to a pre-

existing diagnosis of epilepsy. One male participant was excluded due to his use of medication

which affected the cardiovascular system, and one female participant was excluded because of a

history of simulator sickness. The final analysis therefore included 30 total participants (19

female, 11 male). Participants ranged in age from 17 to 28 years, with an average age of 18.87

years old (SD = 2.46 years).

Detection Performance

Detection performance measures (number of correct detections) were analyzed via a 2

(TASK ORDER: Images First vs. Clips First) X 2 (STIMULUS TYPE: Still Image vs. Video

Clip) mixed ANOVA with repeated measures on the second factor. There was no main effect for

either stimulus type ($F_{(1, 28)} = .143$, $p = .708$) or task order ($F_{(1, 28)} = .009$, $p = .925$) on

detection performance. The hypothesis regarding a main effect for stimulus type was therefore not supported.

As illustrated in Figure C-1, a significant task order by stimulus type interaction on detection performance was observed (F (1, 28) = 5.156, p = .031, η_p^2 = .156). Simple effects tests revealed that participants who were exposed to the static condition first correctly detected more signals that were presented dynamically as opposed to statically (F(15, 28) = 4.58), while participants who viewed the dynamic condition first more successfully detected signals that were presented statically (F(15, 28) = 1.15).

	Static	Dynamic	Dynamic	Static
	Static First		Dynamic First	
■ Series1	20.2	21.133	20.6	21.267
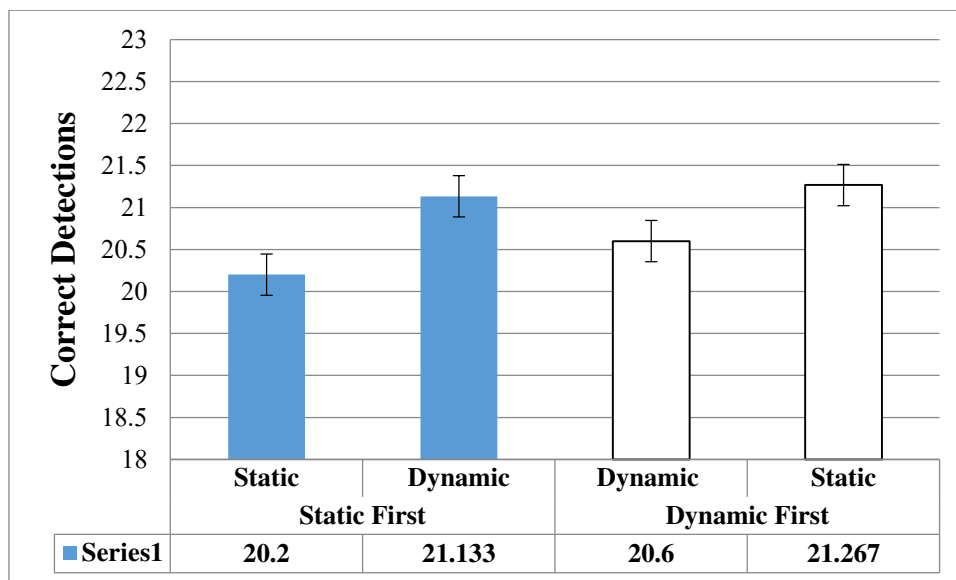
Figure C-1. Significant task order by stimulus type interaction on detection performance. Error bars are standard errors.

Cardiac Activity

Heart rate variability (as measured by standard deviation of all NN intervals (SDNN)) difference scores (phasic – baseline) for all trials in which participants correctly detected the critical signals were analyzed via a 2 (TASK ORDER: Images First vs. Clips First) X 2

146

(STIMULUS TYPE: Still Image vs. Video Clip) mixed ANOVA with repeated measures on the second factor. No main effects for stimulus type ($F (1, 27) = .011$, $p = .918$), or task order ($F (1, 27) = .047$, $p = .830$) were observed. A stimulus type by task order interaction did approach significance ($F(1, 27) = 2.963$, $p = .097$, $\eta_p^2 = .099$) as illustrated in Figure C-2.

	Static	Dynamic	Dynamic	Static
	Static First		Dynamic First	
■Series1	-0.053	-0.05	-0.06	-0.063
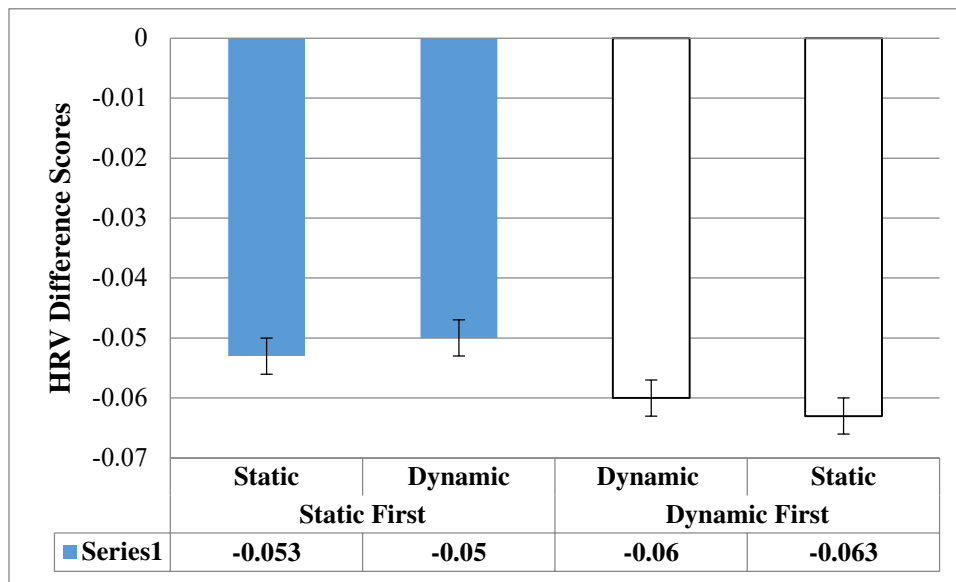
Figure C-2. Non-significant task order by stimulus type interaction. Error bars are standard errors.

Cognitive and Affective States

<u>Dundee Stress State Questionnaire</u>

Univariate analyses conducted on the DSSQ differences (post – pre) scores revealed no significant main effect of task order on either task engagement ($F (1, 28) = .031$, $p = .862$) or worry ($F (1, 28) = .934$, $p = .342$). There was, however, a significant main effect of task order on distress ($F (1, 28) = 6.158$, $p = .019$, $\eta_p^2 = .180$) as shown in Figure C-3. Pairwise comparisons show that participants reported significantly greater distress when completing the static condition first as opposed to the dynamic condition (mean difference = 2.200, $p = .019$). The hypotheses

were therefore not supported. Greater difference scores as measured by the DSSQ were observed

on the distress subscale. However, the hypothesis stated that participants would report greater

levels of distress in response to the dynamic video clips when they did, in fact, report higher

distress in conjunction with the static stimuli.

Figure C-3. Significant main effect of task order on DSSQ distress difference scores. Error bars
are standard errors. The asterisk denotes a statistically significant difference.

A further series of two-tailed t-tests were conducted to test changes on DSSQ difference

scores as a result of participating in the task. Analyses revealed no significant changes in task

engagement (t(29) = -1.520, $p = .139$) or distress (t(29) = .901, $p = .375$). There was, however, a

significant change in worry (t(29) = -2.233, $p = .033$).

NASA Task Load Index

A between-subject univariate ANOVA showed no significant main effect of task order on

the weighted NASA-TLX global workload score (F (1, 28) = .185, $p = .670$). A two-tailed t-test

did, however, reveal that the task imposed significant workload on the participants as measured

by the weighted (t(29) = 10.531, *p* < .0001) global workload score. Given these findings, the hypotheses were partially supported. As a result of completing the task, participants did report experiencing significantly higher global workload. However, workload scores were not influenced by the type of stimulus presentation.

Study 1: 40 Trials

Participants

Twenty-four participants (16 females, 8 males) experienced the 40 trial detection task, and no participants met the exclusion criteria for this study. Participants ranged in age from 17 to 26 years with an average age of 18.50 years (SD = 1.93 years).

Detection Performance

Detection performance measures (number of correct detections) were analyzed via a 2 (TASK ORDER: Images First vs. Clips First) X 2 (STIMULUS TYPE: Still Image vs. Video Clip) mixed ANOVA with repeated measures on the second factor. There were no significant main effects for stimulus type ($F_{(1, 22)}$ = .456, *p* = .506) or task order ($F_{(1, 22)}$ = 2.776, *p* = .110), nor was their interaction significant ($F_{(1, 22)}$ = 2.484, *p* = .129).

Cardiac Activity

Heart rate variability (as measured by SDNN) difference scores (phasic – baseline) for all correct detections were analyzed via a 2 (TASK ORDER: Images First vs. Clips First) X 2 (STIMULUS TYPE: Still Image vs. Video Clip) mixed ANOVA with repeated measures on the second factor. No main effects for stimulus type ($F_{(1, 22)}$ = .014, *p* = .908) or task order ($F_{(1, 22)}$ = .046, *p* = .832) were observed. The stimulus type by task order interaction was also not significant ($F_{(1, 22)}$ = 2.221, *p* = .150).

Cognitive and Affective States

Dundee Stress State Questionnaire

Univariate analyses conducted on the DSSQ differences (post – pre) scores revealed no significant main effect of task order on task engagement (F (1, 24) = .049, p = .827). The effect of task order on distress approached significance (F (1, 24) = 3.654, p = .069). Finally, a significant main effect of task order on worry was observed (F (1, 24) = 6.926, p = .015, η_p^2 = .239) as shown in Figure C-4. Pairwise comparisons show that participants reported significantly greater worry when the dynamic condition was presented first as opposed to the static condition (mean difference = 4.250, p = .015). The hypotheses were therefore not supported. Significantly greater difference scores as measured by the DSSQ were observed on the worry subscale, yet no change in worry was predicted.

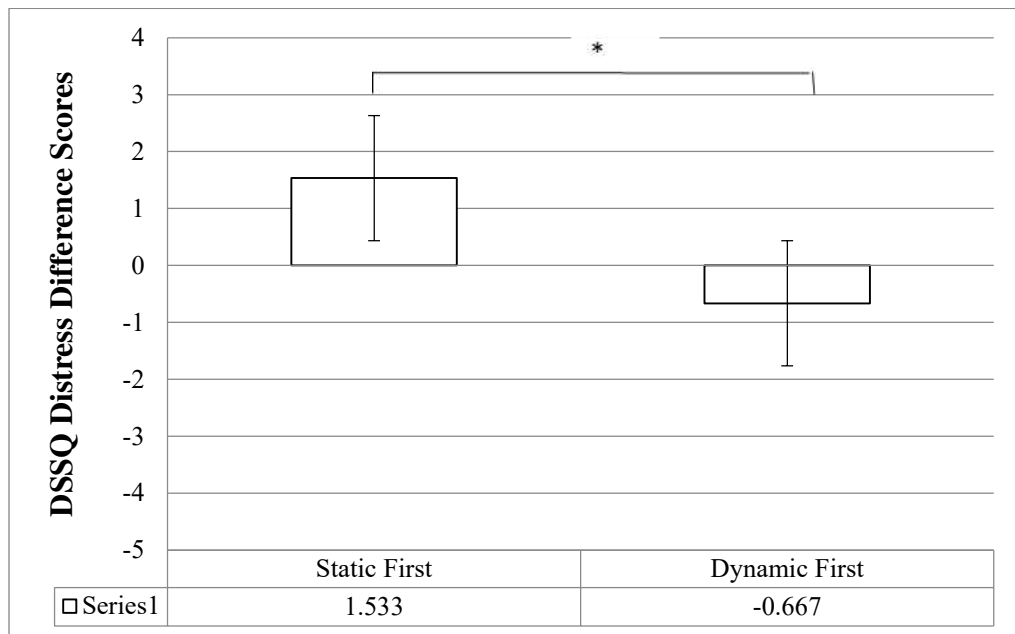|	Static First	Dynamic First
□ Series1	-4	0.25
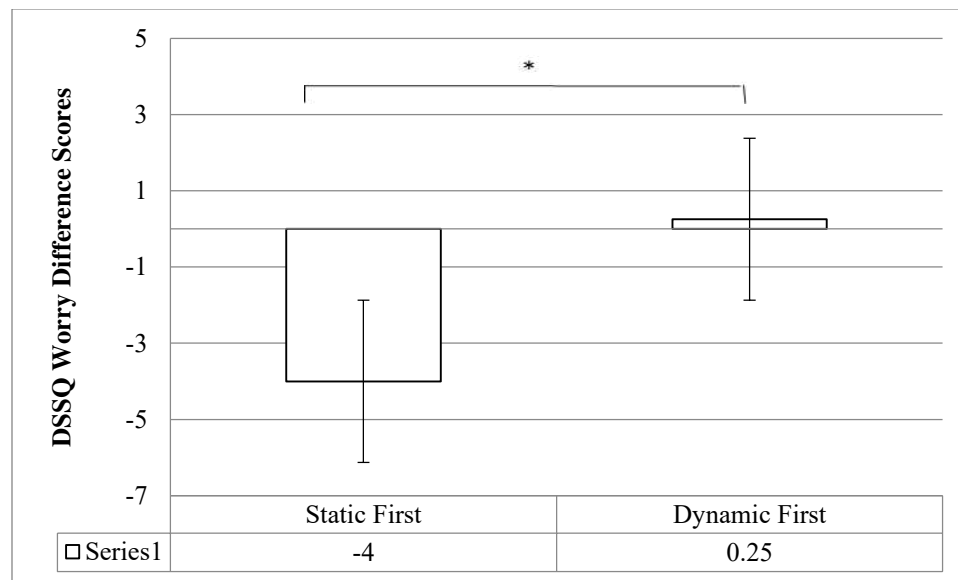
Figure C-4. Significant main effect of task order on DSSQ worry difference scores. Error bars are standard errors. The asterisk denotes a statistically significant difference.

Two-tailed t-tests were conducted to test changes on DSSQ difference scores as a result of participating in the detection task. Analyses revealed no significant changes in task engagement (t(23) = -0.902, p = .376) or distress (t(23) = .452, p = .655). There was, however, a significant change in worry (t(23) = -2.071, p = .050).

NASA Task Load Index

A between-subject univariate ANOVA showed no significant main effect of task order on the weighted NASA-TLX global workload score (F (1, 22) = .377, p = .545). A two-tailed t-test did, however, reveal that the task imposed significant workload on the participants as measured by the weighted (t(23) = 16.488, p < .0001) global workload score (mean = 55.6). Given these findings, the hypotheses were partially supported. As a result of completing the task, participants did report experiencing significantly higher global workload. However, workload scores were not influenced by the type of stimulus presentation.

Study 1: 80 Trials

Considerations

It should be noted that, due to the randomization process, a perfect confound of sex and task order resulted in the scenario whereby all females experienced the static condition first while all males were exposed to the dynamic condition first.

Participants

Nine participants were recruited to complete the detection task with 80 trials. Two female and one male participant were excluded due to epilepsy, a history of simulator sickness, and administration of cardiovascular medication, respectively. Six total participants (3 male, 3

female) with an average age of 20.33 years (SD = 3.83 years) therefore completed the 80 trial detection task. Participants ranged in age from 18 to 28 years old.

Detection Performance

A 2 (TASK ORDER: Images First vs. Clips First) X 2 (STIMULUS TYPE: Still Image vs. Video Clip) mixed ANOVA with repeated measures on the second factor was conducted on the detection performance measures (number of correct detections). No significant main effects for stimulus type (F (1, 4) = .108, p = .759) or task order (F (1, 4) = 1.408, p = .301) were observed. The stimulus type by task order interaction was similarly not significant (F (1, 4) = 2.703, p = .176).

Cardiac Activity

A 2 (TASK ORDER: Images First vs. Clips First) X 2 (STIMULUS TYPE: Still Image vs. Video Clip) mixed ANOVA with repeated measures on the second factor was conducted on the heart rate variability (SDNN) difference scores (phasic – baseline) for all correct detections. No main effects for stimulus type (F (1, 3) = .000, p = .996), or task order (F (1, 3) = .189, p = .693) were observed. The stimulus type by task order interaction was also not significant (F (1, 3) = 1.664, p = .287).

Cognitive and Affective States

Dundee Stress State Questionnaire

Univariate analyses conducted on the DSSQ differences (post – pre) scores revealed no significant main effect of task order on task engagement (F (1, 24) = .049, p = .827), distress (F (1, 24) = 3.654, p = .069), or worry (F (1, 24) = 6.926, p = .015). Two-tailed t-tests conducted on DSSQ difference scores revealed no significant changes in task engagement (t(5) = -1.316, p =

.245), distress (t(5) = 1.190, *p* = .287), or worry (t(5) = -.878, *p* = .420) as a result of participation in the task.

<u>NASA Task Load Index</u>

A between-subjects univariate ANOVA showed no significant main effect of task order on the weighted NASA-TLX global workload score (F (1, 5) = 2.016, *p* = .229). A two-tailed t-test showed that the task imposed significant workload on the participants as measured by the weighted (t (5) = 9.622, *p* < .0001) global workload score (mean = 8.871). A between-subjects univariate ANOVA revealed a significant main effect for task order on the weighted TLX subscale of mental demand (F (1, 4) = 8.112, *p* = .046, η_p^2 = .670). This main effect is illustrated in Figure C-5. Pairwise comparisons specified that participants reported significantly higher mental workload when exposed to the static condition first as opposed to the dynamic condition (mean difference = 14.167).
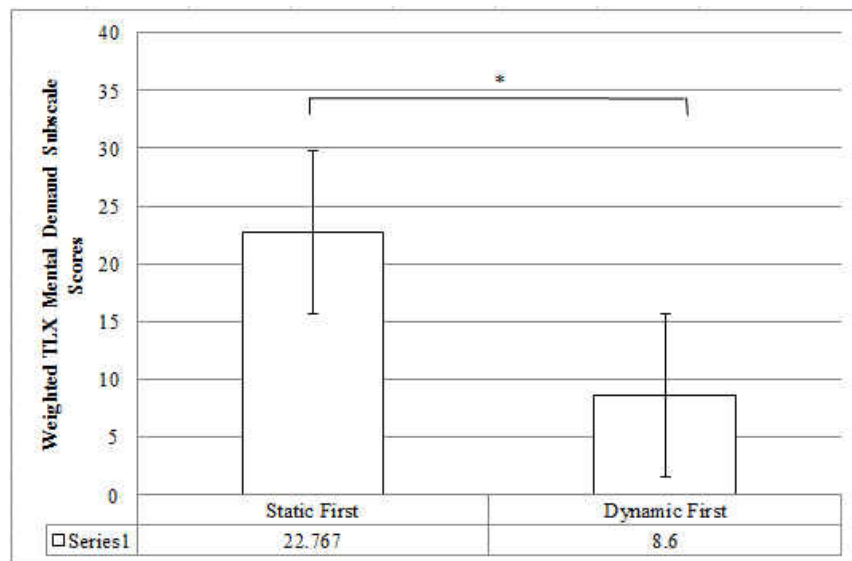

Figure C-5. Significant main effect of task order on weighted mental demand scores, as measured by the NASA-TLX. Error bars are standard errors. The asterisk denotes a statistically significant difference.

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165

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166

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