# A COMPREHENSIVE COMPUTATIONAL MODEL OF SUSTAINED ATTENTION

by

Daniel Gartenberg
A dissertation
Submitted to the
Graduate Faculty
of
George Mason University
in Partial Fulfillment of
The Requirements for the Degree
of
Doctor of Philosophy
Psychology

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Date: ______________________________________ Spring Semester 2016
George Mason University
Fairfax, VA

# A Comprehensive Computational Model of Sustained Attention

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy at George Mason University

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Master of Arts
George Mason University, 2012

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## DEDICATION

This is dedicated to my family – my Father, Mother, Step-Mother, Step-Father, brother, sisters, and grandparents - without their support this work would not be possible.

# ACKNOWLEDGEMENTS

A special thanks to Raja Parasuraman who was very instrumental in the development of this research and who sadly passed on too soon. Raja possessed an encyclopedic knowledge of the literature on sustained attention. I would frequently stop by his office to ask him question and he was always encouraging and inspiring. He is missed.

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## LIST OF EQUATIONS

## LIST OF ABBREVIATIONS

Adaptive Control of Thought – Rational ........ ACT-R
Cognitive Failures Questionnaire ........ CFQ
Event-Related Potential ........ ERP
Epworth Sleepiness Scale ........ ESS
Fatigue-Procedural ........ FP
Fatigue-Procedural Minute Constant ........ FPMC
Fatigue-Procedural Biomathematical Model Constant ........ FPBMC
Goal-Directed-Attention-Time ........ GDAT
Microlapse Theory of Fatigue ........ MTF
Microlapse Theory of Fatigue with Replenishment ........ MTFR
NASA-Task Load Index ........ NASA-TLX
Psychomotor Vigilance Task ........ PVT
Processing Time Errors ........ PTEs
Rest-Procedural Minute Constant ........ RPMC
Sustained Attention to Response Task ........ SART
Traumatic Brain Injuries ........ TBI
Utility Threshold ........ UT
Utility Threshold Biomathematical Model Constant ........ UTBMC
Utility Threshold Minute Constant ........ UTMC

## ABSTRACT

A COMPREHENSIVE COMPUTATIONAL MODEL OF SUSTAINED ATTENTION

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The vigilance decrement is the decline in performance over time that characterizes tasks requiring sustained attention. Resource Theory proposes that the vigilance decrement is due to information processing assets that become depleted with use. Resource theorists must thus identify these assets and the process of how resources are depleted and replenished. The Microlapse Theory of Fatigue (MTF) identifies the resource that is depleted when performing a sustained attention task as the central executive attentional network. The depletion of the central executive network resource results in microlapses or brief gaps in attention that prevent the perception and processing of information. The MTF can explain various effects in the sustained attention literature regarding how resources are depleted. However, the MTF alone cannot explain the event rate effect or the motivation effect because it does not include replenishment mechanisms that can occur during a sustained attention task. To better understand the process of replenishment, participants were assigned to varying event rate and external motivation conditions in a novel paradigm that could measure the perceptual processing of a trial

over time. These stages of processing included when participants looked at the first stimulus, looked at the second stimulus, and responded. In Experiment 1, it was found that the vigilance decrement was more severe for faster event rates, consistent with Resource Theory and counter to the MTF. In Experiment 2, the event rate effect was replicated, but unexpectedly, external motivation did not impact the vigilance decrement. In both experiments it was found that for the stages of processing that involved looking at the stimuli, more slowing was found as event rate increased. Additionally, more slowing was detected earlier in the processing of a trial than later. These results supported the process of microlapses inducing the vigilance decrement due to not having enough time to perceive, encode, and respond to stimuli, as described by the MTF. It was interpreted that the interaction between time-on-task and event rate was due to opportunistic breaks that occurred more frequently in slower event rate conditions. The finding that more slowing occurred earlier in processing was interpreted as evidence for internal rewards related to learning impacting the speed of processing a trial. To explain these findings, I propose the Microlapse Theory of Fatigue with Replenishment (MTFR) a process model similar to MTF, but that includes additional replenishment mechanisms related to opportunistic rest periods and internal rewards. The Microlapse Theory of Fatigue with Replenishment (MTFR) closely correlates to the empirical data and is an important step forward in the effort to build a comprehensive model of sustained attention.

# CHAPTER ONE: INTRODUCTION

## Why Study the Vigilance Decrement?

Due to learning related processes, most tasks are characterized by improved performance with increased task exposure. Conversely, however, sustained attention tasks lead to progressively worse performance over time. This decline in performance over time is called the vigilance decrement (Mackworth, 1948; Davies & Parasuraman, 1982; Warm & Jerison, 1984). The vigilance decrement is typically measured by an operator's accuracy to critical signals that require an infrequent response. When an operator is fatigued and faced with monitoring an environment for a prolonged period of time without a break, the vigilance decrement is particularly severe (Dinges, Orne, Whitehouse, Orne, 1987; Van Dongen, Dinges, 2005; Finomore, Matthews, Shaw, & Warm, 2009; Parasuraman, 1982; Warm & Jerison, 1984).

Understanding the process that causes the vigilance decrement is important to address errors in a number of real-world – and often high risk - settings. People with jobs that are impacted by the vigilance decrement include factory workers, power plant workers, transportation workers, baggage handlers, air traffic controllers, military personnel, and pilots (Mallis, Banks, & Dinges, 2007). These jobs require that workers sustain attention on a monotonous environment for a prolonged amount of time. The vigilance decrement thus has an important safety role in various industries and has been implicated in a number of potentially preventable disasters (Mitler, Carskadon, Czeisler, Dement, Dinges, & Graeber, 1988; Caldwell, 2003; Mallis, Banks, & Dinges, 2007).

Developing a comprehensive process model of sustained attention could help mitigate the errors associated with the vigilance decrement. Ideally, a model could be developed of how the vigilance decrement is impacted by various factors, such as fatigue and time-on-task. Such a model could be used to reduce errors by identifying when an operator should be scheduled, when they should take a break, and how the task load is distributed. A comprehensive model of sustained attention could also improve workplace efficiency by helping to identify the characteristics of sustained attention tasks that make these tasks difficult. This can provide guidance on how to develop sustained attention tasks in order to reduce the likelihood of errors and potentially catastrophic accidents.

**Theoretical Motivation**

The theoretical explanation for the vigilance decrement is typically described at a general level without a quantitative explanation of the cognitive processes involved. A new theory is needed in order to (i) account for the major findings in the literature, (ii) identify the underlying causes and consequences of breakdowns in cognitive performance, and (iii) provide quantitative predictions of performance under the wide variety of existing sustained attention tasks that exist.

The Microlapse Theory of Fatigue (MTF) addresses many of the aforementioned issues by providing a quantitative process account of the vigilance decrement (Gunzelmann et al., 2009; Gunzelmann et al., 2010). The MTF is consistent with Resource Theory, the most prevalent theory in the literature which proposes that sustained attention tasks are strenuous and cause depletion in resources faster than they can be replaced (Davies & Parasuraman, 1982; Warm, Parasuraman, Matthews, 2008). However, the MTF more precisely describes the resource that is depleted when performing sustained attention task and how this resource depletion impacts operator performance.

The MTF identifies central cognition, which can be related to the supervisory attentional network, as the main resource that becomes depleted during performance of a sustained attention task. Namely, the MTF posits that the ability of central cognition to match, select, and execute cognitive actions becomes increasingly difficult when fatigued and when attention must be sustained for a prolonged period of time. The brain region thought to be responsible for the matching, selecting, and executing of cognitive actions are the basal ganglia (Amos, 2000; Houk & Wise, 1995; Stewart, Bekolay, & Eliasmith, 2012). When the basal ganglia are taxed due to fatigue or time-on-task, cognitive actions are not matched, selected, and executed, resulting in a microlapse of attention. With increased fatigue and time-on-task, the likelihood of a microlapse also increases, resulting in fewer cognitive actions from occurring and increased slowing. The MTF posits that this cognitive slowing caused by microlapses results in the inability to process the necessary information to respond. Since microlapses are more likely to occur as time-on-task increases, this process then causes the vigilance decrement.

The MTF was used to describe various effects reported in the literature related to the vigilance decrement. These effects included declines in performance based on sleep deprivation (*i.e.*, the homeostatic component) (Gunzelmann et al., 2009), time of day effects (*i.e.*, the circadian component) (Gunzelmann et al., 2009), and time on task effects (Gunzelmann et al., 2010; Veksler & Gunzelmann, *under review*). The MTF was then extended to explain effects related to the vigilance decrement, including the signal duration effect (Gartenberg, Veksler, Gunzelmann, & Trafton, 2014) and the memory effect (Gartenberg, Gunzelmann, Hassanzadeh, Trafton, *in prep*). The signal duration effect is the finding that there is a greater vigilance decrement under conditions with shorter signal durations. The memory effect is the finding that there is a greater vigilance decrement in tasks that have an increased memory load.

The MTF explained the signal duration effect and the memory effect based on a process that is caused by microlapses having a greater impact on hindering task performance in tasks that have increased time pressure (Gartenberg et al., 2014; Gartenberg et al., *in prep*). A microlapse has a greater impact on performance for tasks that have a shorter stimulus presentation duration or take longer to process due to memory because there is an increased likelihood that the operator will not have enough time to perceive or encode the stimulus. This leads to increased errors over time for conditions with greater memory load and shorter stimulus durations. According to the MTF a similar amount of resource depletion occurs when memory and stimuli presentation are manipulated in sustained attention tasks. However, the vigilance decrement is more severe under conditions that require a greater memory load or have shorter signal durations because a similar depletion of resources differentially impacts task performance when there is less time to process stimili (Gartenberg et al., *in prep*).

While the MTF addressed many of the issues in the sustained attention literature, it cannot explain the event rate effect (Loeb & Binford, 1968; Lanzetta, Dember, Warm, & Berch, 1987; Davies & Parasuraman, 1982) and the motivation effect (Horne & Pettitt, 1985; Bonnefond, Doignon-Camus, Hoeft, Dufour, 2011). The event rate effect refers to the finding that the vigilance decrement can be attenuated when stimuli occur at a slower rate and the motivation effect refers to the finding that the vigilance decrement is attenuated when external incentives are provided. The MTF cannot explain the event rate effect because the processing requirements of different event rate conditions are identical. Additionally, the MTF induces microlapses based on time-on-task and all event rate conditions have the same time-on-tasks. The MTF cannot explain the motivation effect because the model only includes mechanisms that increase the likelihood of a microlapse of attention while engaged in sustained attention.

In this dissertation, I propose a comprehensive theory of vigilance that modifies the MTF by including additional replenishment mechanisms that can be used to account for the event rate effect and the motivation effect. This is theoretically important because there is no good theory of replenishment in regards to the vigilance decrement. Therefore, there is no clear explanation as to why certain tasks can be performed for prolonged period of time without a vigilance decrement, while other tasks show a vigilance decrement.

By including replenishment mechanisms in MTF, it is hypothesized that the model will explain the major effects in the sustained attention literature, an important step in developing a comprehensive model of sustained attention. Another goal of this research is to relate the developed model to the major theories of sustained attention, namely

Resource Theory and Schema Theory.

**Resource Theory**

According to Resource Theory, the mind, like a muscle, becomes tired with use. During a sustained-attention task, the mind becomes fatigued when attention is continuously required, causing cognitive resources to be depleted faster than they can be replaced (Davies & Parasuraman, 1982; Warm, et al., 2008). The dominant theory in the literature is Resource Theory and it has been supported by perceived workload studies (Warm, Dember, and Hancock, 1996), behavioral studies (for meta-analysis reviews see Davies & Parasuraman, 1982 and See, Howe, Warm, Dember, 1995), and neuro-imaging studies (Hitchcock, Warm, Matthews, Dember, Shear, Tripp, Mayleben, Rosa, & Parasuraman, 2003; Helton, et al., 2010; & Lim, Wi, Wang, Detre, Dinges, & Rao, 2010).

Even though sustained attention tasks are frequently quite simple, Resource Theory posits that the perceived workload in these tasks is high because the continuous allocation of attention is stressful (Warm et al., 2008). One of the most commonly used measures of workload in sustained attention tasks is the NASA-Task Load Index (NASA-TLX), a survey that measures workload on a number of dimensions (Hart & Staveland, 1988). Development of the NASA-TLX (Task). The NASA-TLX supported the notion that sustained attention tasks have a high workload, as reported by Warm, et al. (1996), who found that the vigilance decrement was accompanied by a linear increase in overall workload over time. Furthermore, participants reported a high degree of workload, suggesting that sustained attention tasks are difficult and resource demanding (Warm, et al., 1996).

Behavioral studies provide further support for Resource Theory, where it was found that more demanding sustained attention tasks result in a steeper vigilance decrement (for meta-analysis reviews see Davies & Parasuraman, 1982). Resource theorists explain this effect by positing that the more demanding a task, the more it depletes information processing resources. Indeed, a number of studies found a steeper vigilance decrement in more difficult vigilance conditions, including conditions with shorter signal duration (Baker, 1963), increased event rate (Loeb & Binford, 1968; Lanzetta, et al., 1987), increased uncertainty of stimuli (Scerbo et al., 1987), and increased use of memory (for meta-analysis reviews see Davies & Parasuraman, 1982 and See, Howe, Warm, Dember, 1995).

Neuroimaging studies that use transcranial Doppler somnography (TDS), near-infrared spectroscopy (NIRS), and functional magnetic resonance imaging (fMRI) also support Resource Theory (Hitchcock, et al., 2003; Helton, et al., 2010; Lim, et al., 2010). For example, there was a correlated decline in cerebral blood flow over the time-course of performing a sustained attention task (Hitchcock, et al., 2003; Helton, et al., 2010). In particular, the right hemisphere was implicated in declines in vigilance performance (Hitchcock, et al., 2003; Helton, et al., 2010), with bilateral activation during more difficult sustained attention tasks (Helton, et al., 2010). The authors interpreted the correlation between the vigilance decrement and hemovelocity (blood flow in cerebral arteries) as demonstrating that cognitive resource reserves are depleted while performing a sustained attention task, causing a vigilance decrement (Hitchcock, et al., 2003; Helton, et al., 2010).

In further support of Resource Theory, Hitchcock et al. (2003) found that when cues to critical stimulus were provided, the right hemisphere hemovelocity scores declined at a slower rate compared to when no cues were provided. The researchers concluded that conditions that did not have a cue required more cognitive effort, which caused a greater decrease in energy reserves. The decreases in energy reserves resulted in a more severe vigilance decrement in the non-cue condition than in the cue condition (Hitchcock, et al., 2003).

A study that used functional magnetic resonance imaging (fMRI) further implicated the right hemisphere in the depletion of resources in sustained attention tasks (Lim, et al., 2010). Participants performed a 20-minute psychomotor vigilance task (PVT), which required responding as quickly as possible when a stimulus appeared. Reaction time slowed as the task progressed and mental fatigue was rated as higher after the task than before it. In support of the right cerebral lateralization that accompanies the vigilance decrement, there was increased activation of the right fronto-parietal attentional network that lateralized to the basal ganglia and sensorimotor cortices when performing the PVT. In further support of the notion that the PVT drained resources, the cerebral blood flow in these networks decreased with performance declines on the PVT. The experiment supports Resource Theory because it concluded that the fronto-parietal network was less active after the vigil compared to before and by providing evidence that resources related to the basal ganglia were depleted by the task.

Taken together, converging evidence supports Resource Theory, including the increase in workload that accompanies the vigilance decrement; the behavioral studies which demonstrate that more difficult sustained attention tasks induce a steeper decrement; and the neuroimaging studies, which show that cerebral blood flow declines when performing a sustained attention task. The neuroimaging studies in particular support Resource Theory because resources can be measured more directly. While the exact construct defining a resource is not clearly specified by the theory, the imaging studies suggest that one of the major resources depleted in sustained attention tasks is related to the basal ganglia, a subcortical structure thought to be responsible for pattern recognition across the activation of the cortex (Amos, 2000; Houk & Wise, 1995; Stewart, et al., 2012).

**Specifying the Resource**

One of the major issues with Resource Theory is the difficulty in defining the behavioral and cognitive construct of a resource. The vigilance taxonomy was created as a way for resource theorists to better distinguish the resource that is depleted when performing a sustained attention task (see Figure 1) (Davies & Parasuraman, 1982). After conducting a meta-analysis of 42 vigilance studies, Davies and Parasuraman (1982) created the vigilance taxonomy. This meta-analysis found that four factors impacted the vigilance decrement. These factors included the extent that memory was involved, the event rate (*i.e.,* the frequency that stimuli are presented), the modality (*i.e.,* visual or auditory), and the source complexity (*i.e.,* the number of displays that are required to be monitored). Tasks that had a faster event rate, multiple sources of complexity, and a greater memory load were more likely to have a vigilance decrement. Both types of modalities, visual and auditory, were found to induce the vigilance decrement, as was later demonstrated in a study where visual and auditory stimuli were equated for difficulty (Shaw, Warm, Finomore, Tripp, Matthews, Weiler, Parasuraman, 2009). This has led some researchers to suggest that there are other resources in addition to an attentional resource, namely a memory resource. Evidence for a memory resource was supported in a subsequent meta-analysis (See, Howe, Warm, Dember, 1995).

Most resource theorists agree that the supervisory attentional network is the major source of resource depletion, which in turn results in the vigilance decrement (Parasuraman & Davies, 1982; Warm & Dember, 1998; Warm et al., 2008). However, evidence from behavioral research has led some researchers to conclude that there is a memory resource in addition to a supervisory attentional resource (Parasuraman, 1979; See et al., 1995; Caggiano & Parasuraman, 2004), a declarative memory resource (Halverson, Gunzelmann, Moore, & Van Dongen, 2010), and independent resources that relate to the visual and auditory modalities (Davies & Parasuraman, 1982; Wickens, 1984). Warm and Dember (1998) argue that any factors that increase the demand on overall attention results in a greater resource depletion. Clearly, there are varying perspectives regarding what is a resource and how such resources are depleted.

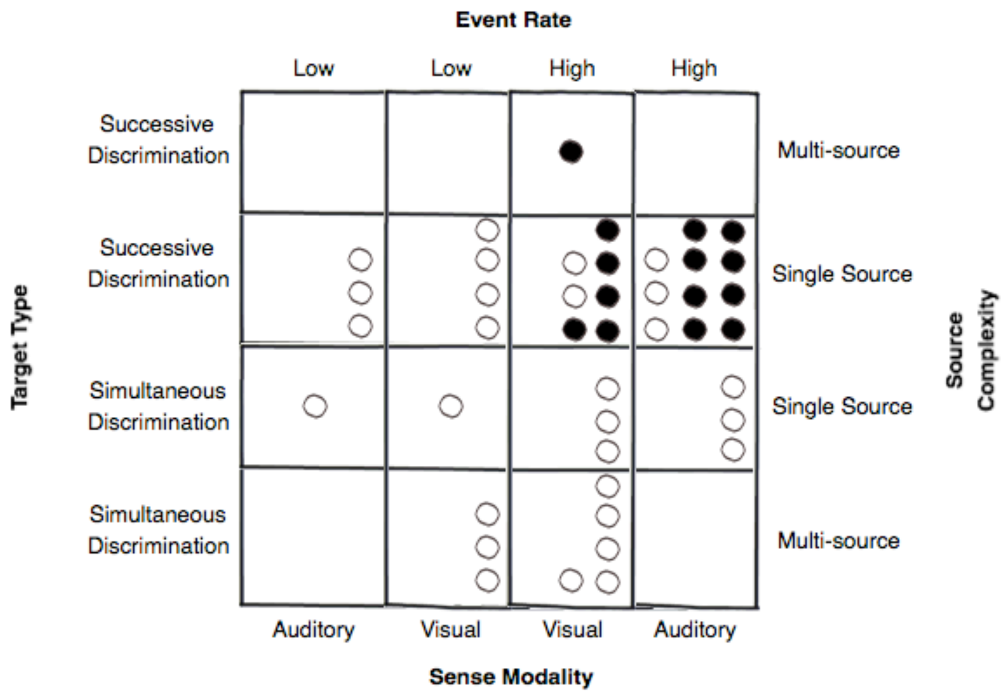



**Figure 1. Vigilance Taxonomy. An image of the vigilance taxonomy described by Davies & Parasuraman 1982 where the taxonomy is comprised by event rate, source complexity, memory (successive versus simultaneous), and sense modality. The filled in circles represent the presence of the vigilance decrement and the open circles represent the absence of the vigilance decrement by experiment. The vigilance decrement was measured using a signal detection metric.**

**Schema Theory**

In contrast to Resource Theory, Schema Theory posits that the vigilance decrement is due to under-arousal rather than stress and over-arousal (Robertson, et al., 1997; Manly et al., 1999). Schema Theory is consistent with theories that posit that the decrement is due to the unstimulating and repetitive nature of sustained attention tasks (Frankmann & Adams, 1962; Loeb & Alluisi, 1984). Both of these conceptualizations are referred to here as Schema Theory because they share a similar underlying mechanism. The mechanism described by Manley et al. (1999) involves the entrenchment of well-learned, routine responses that are represented as schemas. The activation of these schemas is driven by both internal cues and the strength of the association of the cue and a pattern of behavior. If a task is highly routinized, attentional control is required to suppress the schema and provide an alternative response. As a sustained attention task progresses, it becomes increasingly difficult for attentional control to suppress the schema and the vigilance decrement occurs.

Evidence in support of Schema Theory comes from performance on a task called the Sustained Attention to Response Task (SART). In typical sustained attention tasks critical stimuli requiring a response occur infrequently. The SART reverses the hit frequency of typical sustained attention tasks by requiring the participant to respond to non-critical stimuli that occur frequently, and then to withhold a response when a critical stimulus appears. Using this paradigm Robertson et al. (1997) found that participants who experienced Traumatic Brain Injuries (TBI) performed worse on the task over time than participants who did not have TBI. It was also found that in a non-TBI population, individuals who responded as highly absentminded on the Cognitive Failures Questionnaire (CFQ) (Broadbent, Cooper, FitzGerald, & Parkes, 1982) were more likely to perform worse on the SART. The explanation form Schema Theory as to why participants who have TBI and who score highly on the CFQ nonetheless perform worse on the SART is that these individuals have a greater difficulty in using attentional control to consciously process stimuli that are repetitive and non-arousing.

Manley et al. (1999) found further support for the notion that the vigilance decrement is due to attentional control and the routinization of behavior by comparing a typical

SART task with a modified SART task. The modified SART task had 50% of its trials as non-critical trials that required a response, as opposed to a typical SART task where ~89% of the trials are non-critical trials. By manipulating the SART in this way, Manley et al. (1999) discovered how routinization impacted the vigilance decrement. In a series of experiments it was found that performance on critical trials was worse for the typical SART task than the modified SART. Again, it was found that there was a correlation between the vigilance decrement and the CFQ. Manley et al. (1999) explained their findings by proposing that the vigilance decrement is due to inefficiencies in the maintenance of attentional control. In this interpretation of the vigilance decrement a supervisory attentional system, similar to the system described by Norman and Shallice (1980) and Cooper, Ruh, and Mareschal (2015), is hindered when a task is highly routinized, which particularly impacts patients who have TBI and individuals ranking highly on the CFQ. The result of having an ineffectual or imperfect supervisory attentional system is that exposure to repetitive non-critical stimuli results in an increasingly reduced activation of the task and a greater routinization of behavior. Incorrect responses increase when the supervisory attentional system cannot override this routinization.

### The Problem with Resource Theory and Schema Theory

Neither Resource Theory nor Schema Theory can make quantitative predictions regarding the vigilance decrement across different types of sustained attention tasks and differing levels of operator fatigue. Nor can either theory make explicit predictions regarding the specific factors that impact the depletion and replenishment of resources and how these factors impact the perceptual processing of the human operator.

Another issue with Resource Theory is that any effect found in the vigilance literature could be explained by the inclusion of another resource, rendering the theory unfalsifiable. For example, in previous research it was found that the vigilance decrement was more severe as memory load increased (Davies & Parasuraman, 1982; See et al., 1995), and in response, it was argued by resource theorists that there is an additional memory resource. A similar account can be described for any factor that is found to result in a more severe vigilance decrement.

Schema Theory also cannot explain various effects in the vigilance literature. For example, Schema Theory makes incorrect predictions on the neuroimaging studies on sustained attention, where the theory predicts a decrease in cerebral blood flow over time because of attention being withdrawn from the task. Schema Theory also does not explicitly make a prediction regarding the event rate effect found in the behavioral studies of the vigilance decrement. One possibility is that Schema Theory predicts that the vigilance decrement is identical across different event rates because they have identical percentages of neutral and critical trials, resulting in a similar routinization between conditions. However, in previous literature, the vigilance decrement was steeper for faster event rate conditions (Loeb & Binford, 1968; Lanzetta, Dember, Warm, & Berch, 1987; Davies & Parasuraman, 1982).

**The Microlapse Theory of Fatigue: A Process Model of Vigilance**

The Microlapse Theory of Fatigue (MTF) addresses many of the issues in the sustained attention literature by providing a process account of the vigilance decrement that is instantiated as a computational model. The computational model is integrated with the Adaptive Control of Thought – Rational (ACT-R) cognitive architecture (Anderson, 2007), which can be used to model the wide assortment of sustained attention tasks that exist in the literature. Importantly, MTF identifies central cognition as the main resource that is depleted when performing a sustained attention task, which implicates the part of the brain, called the basal ganglia (Gunzelmann et al., 2009; Gunzelmann et al., 2010). When central cognition is fatigued because of the continual need to match, select, and execute cognitive actions, it becomes increasingly more difficult for a cognitive action to be selected, resulting in a microlapse of attention and slowing of cognition.

Evidence for the role of central cognitions as the primary resource that is depleted in sustained attention tasks is consistent with the previously discussed fMRI study that showed increased activation of the right fronto-parietal attentional network that lateralized to the basal ganglia (Lim et al., 2010). Like central cognition, the basal ganglia are thought to be responsible for the matching, selecting, and executing of cognitive actions (Amos, 2000; Houk & Wise, 1995; Stewart, et al., 2012). According to the MTF, sustained attention tasks induce the vigilance decrement because the basal ganglia become taxed due to the requirement of the operator to monitor the environment and repeatedly make cognitive decisions (Veksler & Gunzelmann, *under revision*).

The MTF provides a process description of how central cognition is impacted by the continuous need to make cognitive decisions. When required to continuously make decisions, according to MTF, central cognition is overloaded such that cognitive actions are less likely to occur. This then induces brief disruptions in goal-directed processing called microlapses. Time-on-task and fatigue processes impact the likelihood that a microlapse will occur, so increased fatigue and time-on-task cause greater difficulty for the operator to select and execute cognitive actions. The inability to select and execute cognitive actions produces small gaps in attention and goal-directed processing by reducing the value given to cognitive actions. As a result, it may take longer for a cognitive action to occur. In the case of extreme fatigue, it may take longer than 30 seconds for a cognitive response (Gunzelmann et al., 2009), with these long gaps in attention being increasingly likely with increased time-on-task.

The MTF is integrated within the ACT-R cognitive architecture (Anderson, 2007) (see Figure 2) making it possible for the development of a single model able to make quantitative predictions about human performance for different types of sustained attention tasks. ACT-R is a general theory of cognition that suggests a number of modules that incorporate theories that represent different components of cognition (Anderson, 2007). This may provide a framework for the way information is processed, in addition to the time-course of processing. Among the modules included in ACT-R are a central cognition system that can coordinate actions; visual and auditory modules for motor action; audition; vision; goal maintenance; declarative knowledge, procedural knowledge, and imaginal knowledge. Because ACT-R provides a theoretical framework for how information is processed, integrating MTF with ACT-R makes it possible to develop a model that can be applied across various sustained attention tasks.

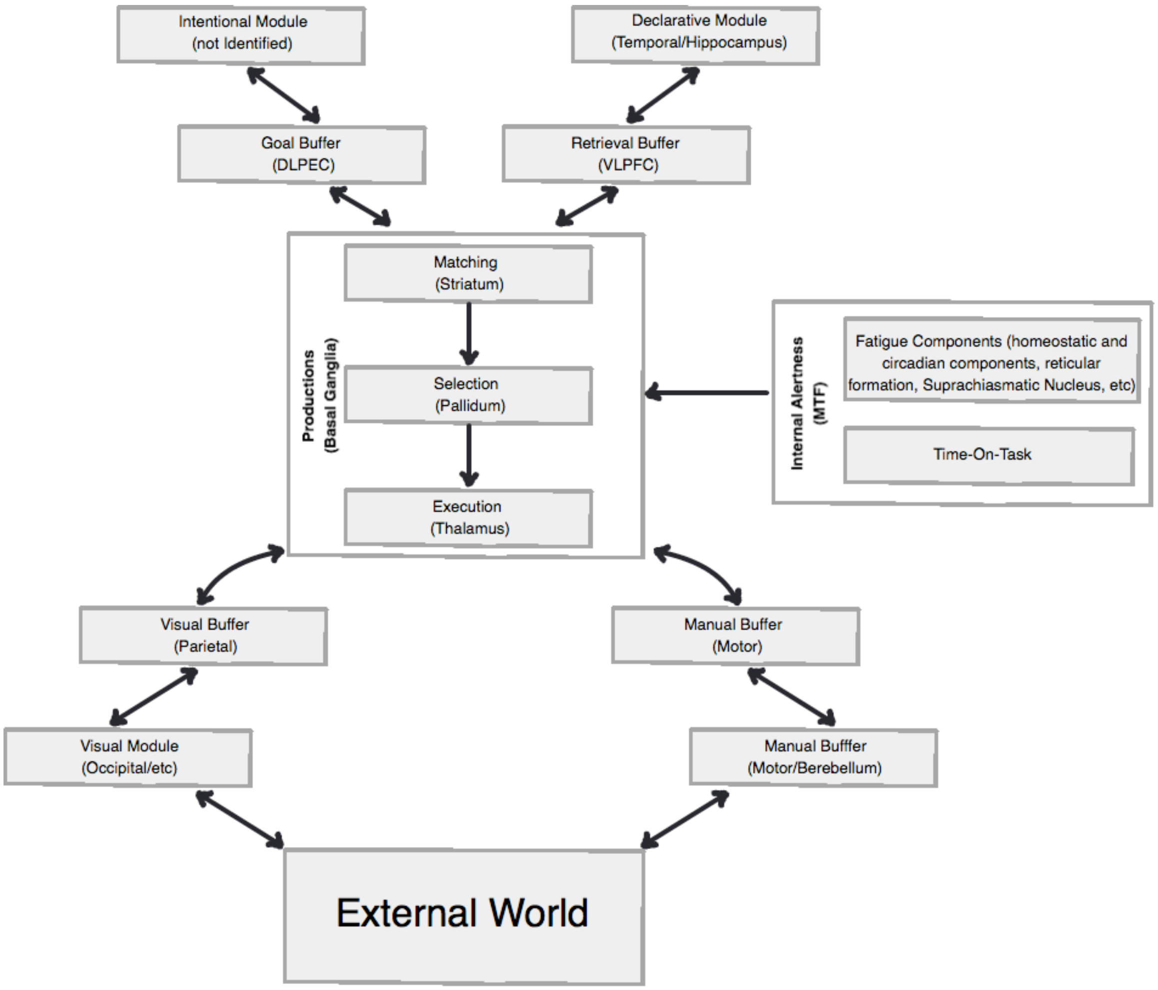



**Figure 2. ACT-R Schematic With MTF modification. Schematic image of the ACT-R cognitive architecture with the MTF modification including the mapping of the architecture to specific brain regions.**

The MTF modifies ACT-R by positing that fatigue and time-on-task impact the likelihood that a cognitive action will occur. In ACT-R, a cognitive action is referred to as a production. Every production has a given value, or utility, that must surpass a threshold in order to occur. The MTF proposes an additional scalar to the production utility equation of ACT-R. This scalar is impacted by fatigue mechanisms based on a biomathematical model of fatigue that takes into account the homeostatic and circadian components of sleep (Hursh, Redmond, Johnson, Thorne, Belenky, Balkin, Storm, Miller, & Eddy, 2004; McCauley, Kalachev, Mollicone, Banks, Dinges, & Van Dongen, 2013). Additionally, the scalar is impacted by time-on-task, which is constrained using a power function, following existing research that has mathematically quantified the nature of the vigilance decrement (Giambra & Quilter, 1987).

For example, consider a sustained attention task that requires the use of a cognitive action, or production, to occur on a given trial in order for the participant to respond appropriately. A production in ACT-R is a procedural fule such as: 'IF a stimulus is present THEN get its visual location and make a request to declarative memory'. In ACT-R, a production must be above a given threshold in order to fire (see Figure 3). According to MTF, due to the need to continuously make decisions in sustained attention tasks, over time, production utilities decrease (Gunzelmann et al., 2009). Thus, in Figure 3, when the production utility, which can also be impacted by noise, falls below the utility threshold, a microlapse occurs. Given enough microlapses, the participants' cognition will slow to the point that the task will not be performed.

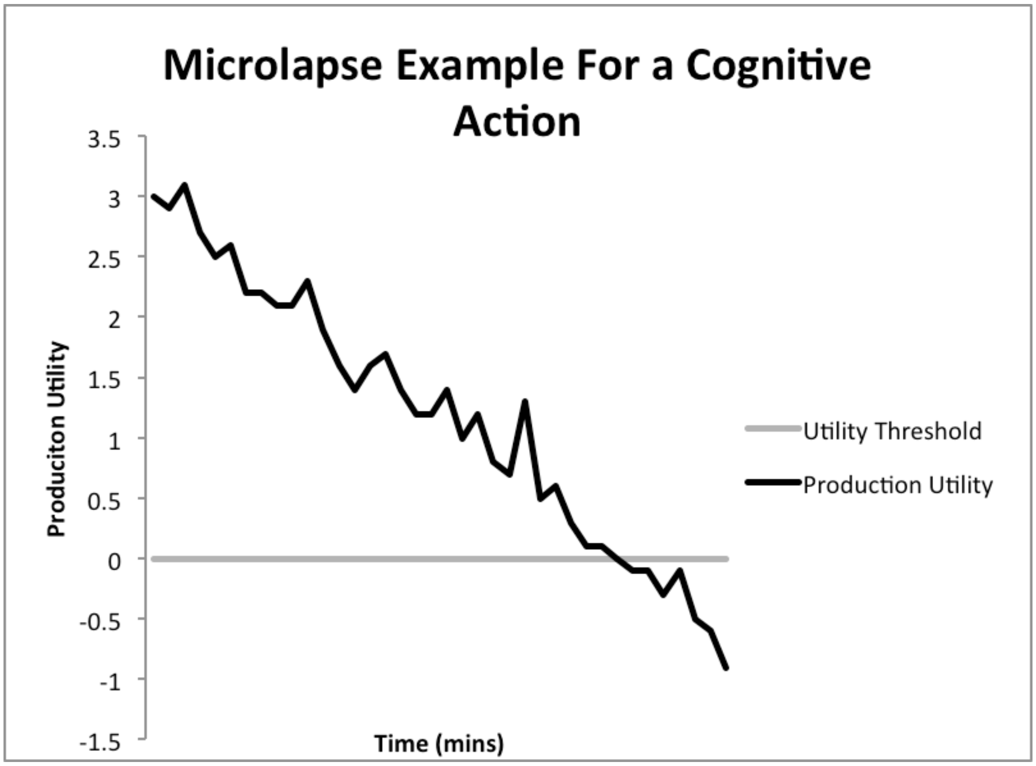



**Figure 3. Microlapse Example for a Cognitive Action. The production utility starts above the utility threshold, meaning that it will fire. However, overtime it falls below the utility threshold. When this happens, at point 0 on the y-axis, a microlapse of attention occurs.**

In order to compensate for the impact of microlapses, Gunzelmann et al. (2009) proposed an additional mechanism to account for the role of effort. Recall that a production fires when its production utility is above a given threshold. Therefore, to compensate for low production utilities, Gunzelmann et al. (2009) stated that effort can be used to decrease the utility threshold based on the same mechanisms that the production utility was decremented. By reducing the production utility threshold, productions are more likely to fire and microlapses are less likely to occur. However, this also has the effect of increasing the likelihood that inappropriate actions will occur.

This may provide an explanation for increased false alarms when performing a sustained attention task (Gunzelmann et al., 2009). The effort mechanism of the MTF therefore predicts that as effort increases, there will be more instances of responding appropriately to critical stimuli, yet this will be accompanied by more false alarms.

**The Microlapse Theory of Fatigue Explanation of the Vigilance Taxonomy**

Of particular relevance to this research is the recent effort to extend MTF to explain the vigilance decrement. Veksler and Gunzelmann (*under revision*) demonstrated that the same mechanisms used by Gunzelmann et al. (2010) to explain time-on-task effects when performing the PVT could account for performance decrements in a conventional sustained attention task, called the Mackworth Clock Task (Mackworth, 1948). The MTF was then extended to explain other effects in the sustained attention literature and the vigilance taxonomy, including the signal duration effect (Gartenberg et al., 2014) and the memory effect (Gartenberg et al., 2015; Gartenberg et al., *in prep*).

The MTF was applied to the signal duration effect using a seminal experiment by Baker (1963), which parametrically manipulated signal duration of critical signals. In this study, the operator was asked to monitor a clock-face display for two hours, where a second hand on the clock-face moved in a continual swipe motion. The second hand periodically stopped for 200 ms, 300 ms, 400 ms, 600 ms, or 800 ms. The operator was asked to respond when they detected that the second hand stopped. Baker (1963) found that performance declined at a faster rate as signal duration decreased, which was then modeled by the MTF (see Figure 4). Gartenberg et al. (2014) explained that MTF replicated the effect based on the dynamics of cognition and the task requirements.

When the task requirements involved shorter stimuli durations, cognitive processes were less likely to be able to encode the stimuli due to the impact of microlapses. This interaction between signal duration and time-on-task was due to the differential impact that microlapses have on performance for shorter signal duration conditions. That is, when the stimulus duration is shorter, relatively small numbers of microlapses will cause the model to fail to perceive and encode the stimulus leading to a more precipitous decline in performance for shorter stimuli durations than longer stimuli durations, despite the similar depletion of resources between stimuli duration conditions.

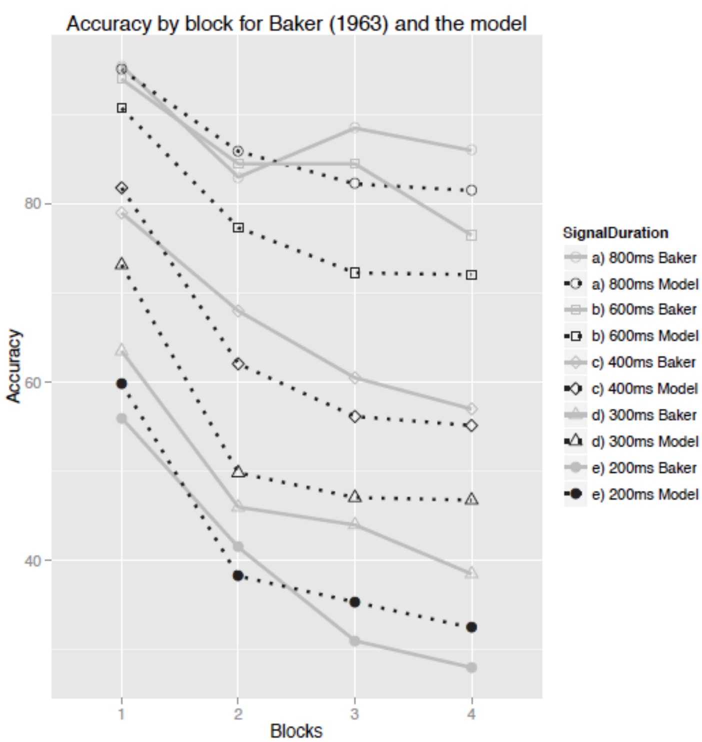



**Figure 4. MTF Model Results of the Signal Duration Effect. Gartenberg et al. (2014) successfully modeled the signal duration effect using the MTF; where the model provided good fit to the data ($R^2$ = .94, *RMSE* = 5.68%).**

Gartenberg, et al. (*in prep*) described a similar process as Gartenberg et al. (2014) to explain the memory distinction in the vigilance taxonomy, where no memory effect was found when the processing time of the stimuli were controlled. Recall that the memory distinction refers to tasks that involve more memory (*i.e.,* successive tasks) showing a steeper vigilance decrement than tasks that involve less memory (*i.e.,* simultaneous tasks) (Davies & Parasuraman, 1982; See et al., 1995). Gartenberg et al. (*in prep*) used a new task that controlled for how long it took participants to process the stimuli and found no difference between simultaneous and successive tasks. The explanation as to why a memory effect was not found for this research paradigm is that successive tasks typically take a longer amount of time to encode due to the additional memory imperative of these tasks.

The MTF can thus be used to explain the memory effect reported in the literature by positing that the memory effect only exists when the stimuli are not adequately controlled for processing time requirements. When tasks take longer to encode, microlapses have a greater impact on performance. Since the processing time for the stimuli was controlled in Gartenberg et al.'s (*in prep*) study using a thresholding procedure, no memory distinction was found. Consistent with this interpretation, in other research it was found that simultaneous tasks can induce a steeper vigilance decrement than successive memory tasks when perceptual demands for the simultaneous tasks are high (Grubb, Warm, Dember and Berch, 1995). Taken together, these findings suggest that typical sustained attention tasks do not drain an additional resource that is related to memory.

Gartenberg et al. (*in prep*) refer to the types of errors that occur when the participant does not have enough time to process the stimuli as processing time errors (PTEs). PTEs occur when the stimuli are presented for too short an amount of time for the operator to process them, which is more likely to occur when microlapses increase. As previously described, tasks with shorter signal durations or those requiring more memory show a steeper vigilance decrement because microlapses differential impact these conditions, thereby increasing the likelihood of PTEs. For example, if the signal duration of a sustained attention task is 800 ms, a single microlapse is less likely to result in the participant not being able to process the stimulus than in a sustained attention task where the signal duration is 200 ms. This mechanism where microlapses impact conditions that take longer to process to a greater extent than conditions that are shorter to process can be extended to explain other effects in the sustained attention literature such as the signal saliency effect, where there is a steeper vigilance decrement for less salient stimuli, the source modality effect, and the source complexity effect. The reason that PTEs can explain these effects is based on the assumption that it takes longer to process less salient stimuli, stimuli that involve a modality that takes more time, and stimuli that are more complex.

However, PTEs cannot explain effects related to replenishment, including the event rate effect and the motivation effect. PTEs cannot explain the event rate effect because the processing time of the stimuli is identical between different event rate conditions. Similarly, the processing time of the stimuli is identical in experiments that manipulate motivation, yet in previous research it was found that more motivated participants experience an attenuation of the vigilance decrement (Horne & Pettitt, 1985; Bonnefond, et al., 2011).

## Extending the Microlapse Theory of Fatigue to the Event Rate Effect

Because the MTF decrements performance based on time-on-task, the MTF predicts that a similar decline in performance will occur between different event rate conditions – since differing event rate conditions have the same time-on-task. Yet the event rate feature of sustained attention tasks, which require continuously sampling the environment at differing rates, may be one of the distinguishing features of sustained attention tasks that make them different from other types of tasks that require continuous attention. Fast event rates mean that the operator is required to sample the environment and select productions more frequently and are less likely to have the opportunity to take "task-contingent" timeouts (Mark, Warm, & Huston, 1987). For example, in low event-rate tasks, participants respond to the stimuli and then have time between their response and the next stimuli to take a break.

In this dissertation, a modified version of the MTF is proposed called the Microlapse Theory of Fatigue with Replenishment (MTFR), which replaces the time-on-task mechanism described in MTF with a new concept: Goal-Directed-Attention-Time (GDAT). GDAT increases the likelihood of a microlapse when attention is allocated to the task and decreases the likelihood of a microlapse when attention is not allocated to the task. So the more time that is spend on task-contingent breaks, the lower the likelihood that a microlapse will occur. Notably, this means that there is a replenishment mechanism built into the MTFR where if no cognitive action is required by the task, then this constitutes a "task-contingent" timeout. These attention breaks, or task-contingent timeouts result in increasing the production utility and fewer microlapses of attention.

Taking task contingent timeouts has a similar impact as the process of sleep described by the biomathematical component of the MTF and the MTFR. When Gunzelmann et al. (2009) developed the MTF, they demonstrated that sleep related processes impact the likelihood of a microlapse. MTFR posits that in addition to sleep, task contingent time-outs can increase production utility. Increasing production utility reduces the likelihood of a microlapse, thereby resulting in an attenuation of the vigilance decrement due to less PCEs.

Recall that the MTF states that the depletion of resources that resource theorists describe has to do with the overuse of the basal ganglia. The basal ganglia are overused in sustained attention tasks because a feature of these tasks is that they overload goal directed attention. The MTFR alters MTF by creating the concept of GDAT and replacing the time-on-task variable of MTF with GDAT. The result of replacing time-on-task with GDAT is that MTFR predicts that faster event rate sustained attention tasks will show a steeper decrement, while the MTF does not make this prediction. In order to support the microlapse process that underlies MTFR, MTFR also posits that conditions that include faster event rates will have more slowing throughout each stage of processing due to more microlapses occurring in these conditions.

**Extending the Microlapse Theory of Fatigue to the Motivation Effect**

While the effort mechanism built into the MTF can explain the motivation effect found in the vigilance literature, it makes a nuanced prediction regarding the impact of effort. Specifically, the MTF predicts that increased effort will attenuate the vigilance decrement, but also increase false alarms. However, in previous research, motivation attenuated the vigilance decrement, without increasing false alarms (Horne & Pettitt, 1985; Bonnefond, et al., 2011).

In Horne and Pettitt's (1985) study of motivation, sleep deprived participants performed a modified version of the Wilkinson Auditory Vigilance Task (Wilkinson, 1968) and were either provided a monetary incentive for good performance, or were not provided with any monetary reward. Those who were assigned to the reward condition were able to maintain performance on both critical trials and neutral trials at baseline levels for up to 36 hours of sleep deprivation; those who did not receive a reward did not demonstrate a comparable performance.

In a study that used non-sleep deprived participants for 60 minutes of sustained attention, participants who were told that they were being evaluated were able to maintain stable performance for hits and false alarms, while participants who were not told they were being evaluated experienced the typical vigilance decrement (Bonnefond, et al., 2011). Event-Related Potential (ERP) analysis localized this interaction between motivation and time-on-task to the amplitude of the correct response negativity (CRN) ERP, which is associated with cognitive control on correct responses.

The MTF has not yet been used to explain the motivation effect, but ACT-R includes a built in mechanism related to reward that can explain this effect. In ACT-R, learning occurs via the well-established temporal difference learning algorithm, in which tasks are learned based on an observation of success or failure of cognitive actions on the task (Sutton & Barto, 1998). This is instantiated in ACT-R as utility learning. In utility learning, a production is gradually adjusted until it matches the overall reward that is received based on the proximity of the reward and the production in time. Given that participants experience a greater reward when they are provided monetary incentives (Horne et al., 1985) and are told they are being monitored (Bonnefond, et al., 2011), a prediction based on ACT-R's utility learning mechanism is that this will cause fewer microlapses. In ACT-R's utility learning algorithm, increased rewards result in higher production utility values. Since higher production utility values decreases the likelihood of a microlapse, this suggests that utility learning can act as an additional replenishment mechanism that can attenuate the vigilance decrement.

A feature of utility learning in ACT-R is that rewards are backpropagated to productions that came before it. More recent productions relative to the reward receive a higher reward than those that occurred earlier. As a result, the production utility for more recent productions in relation to the reward receives a relatively higher production utility. An example progression of productions in a sustained attention task could be:

**Table 1. ACT-R example of productions in a sustained attention task. The italicized production names provide a brief description of the function of the productions and the production description provides the If / Then logic of the production in ACT-R.**

| Production Names | Production Descriptions |
|---|---|
| *attend* | **IF** a stimulus is present, **THEN** attend to it by getting its visual location and make a retrieval to the declarative module |
| *encode* | **IF** the declarative module is not busy, **THEN** encode the stimulus and determine if it is a critical trial |
| *respond* | **IF** what is encoded is a critical trial, **THEN** respond by pressing the spacebar |

Assuming that a reward occurs when both stimuli are successfully encoded, then the encode production will receive a greater amount of the reward than the attend production, and therefore will have a higher production utility relative to the attend production.

Therefore, using utility learning in ACT-R can have two main impacts on a model of vigilance. If more motivation is given in one sustained attention task than another, the model predicts that performance will be better in the sustained attention task that had greater motivation because more rewards are propagated to productions, resulting in higher production utilities and fewer microlapses.

Utility learning also posits a nuanced pattern in the processing of a vigilance trial, where more recent productions in relation to when a reward occurs will show fewer microlapses. The reason utility learning posits that more recent productions in relation to a reward will show fewer microlapses is because cognitive actions that are closer in temporal proximity to the reward get a greater proportion of the reward than cognitive actions that occur farther away from the reward in time. As a result, productions closer to the reward are more likely to have a higher production utility, meaning that these productions are more likely to be above the production utility threshold and that a microlapse is less likely to occur.

**Current Study**

This study was designed to determine if additional replenishment mechanisms are needed in a comprehensive computational model of sustained attention. In order to explore this, the event rate at which stimuli appeared and external motivation were manipulated. It was hypothesized based on the MTFR that additional replenishment mechanisms are required in order to generate the hypothesized interaction between event rate and time-on-task, where the vigilance decrement is more severe over time in faster event rate conditions. The MTFR also posits more microlapses over time in faster event rate conditions, that internal rewards when performing a given task can impact the likelihood that a microlapse will occur, and that external rewards can also have an impact on these gaps of attention through a similar process.

Experiment 1 was designed to explore the event rate effect and the proposed task break modification to the MTF by parametrically manipulating event rate. Also in Experiment 1, the pattern of perceptual processing of a vigilance trial was analyzed in order to determine where cognitive slowing occurs in a given sustained attention task trial. By measuring slowing using an eye tracker and by designing an experiment that separated a given trial into three stages of processing, the prevalence and timing of microlapses could be inferred.

Experiment 2 was designed to determine if the effects found in Experiment 1 were replicated. In addition, Experiment 2 was designed to determine how external motivation impacts the vigilance decrement. In Experiment 2, external motivation was manipulated by providing some participants with monetary incentives in addition to showing participants that they were being monitored.

**Event Rate Performance Hypotheses**

The MTFR and Resource theory both predict that there will be a steeper vigilance decrement in faster event rate conditions (see Table 2 for an overview of the hypotheses). The MTFR predicts this interaction between time-on-task and event rate because in slower event rate conditions participants can replenish more resources by taking more opportunistic task breaks in slower event rate conditions. This is similar to the "task contingent time-outs" described by Mark, Warm, and Huston (1987). By replenishing more resource during these task breaks, participants experience fewer micro-lapses of attention in the slower event rate conditions. Thus, in the slower event rate conditions, participants are more likely to be able to process and respond to the necessary information in order to make a correct response.

Resource Theory also predicts this interaction, yet the theory is less specific on the process by which the attenuation of the vigilance decrement occurs for slower event rate conditions. According to Resource Theory, when stimuli appear less frequently, such as is the case with slower event rates, less attentional resources are required to perform the task (Loeb & Binford, 1968; Lanzetta, et al., 1987; Davies & Parasuraman, 1982). Fewer resources being allocated to the task results in an attenuation of the vigilance decrement for slower event rate conditions.

The MTF does not make the prediction that slower event rate conditions produce a steeper vigilance decrement because the theory decrements resources based on time-on-task. Because the theory induces microlapses based on the variable of time-on-task, it does consider that participants take opportunistic breaks from the task when attention is not required.

It is unclear what prediction Schema Theory makes regarding the interaction between event rate and time-on-task. Schema Theory states that the vigilance decrement is induced by task routinization. One possible prediction from Schema Theory is therefore that there will not be an interaction between event rate and time-on-task because in typical manipulations of event rate, all three event rate conditions have the same percentage of critical trials (Loeb & Binford, 1968; Lanzetta, et al., 1987). However, an alternative interpretation is that since in order to control for the percentage of critical trials there were overall more neutral trials in the fast event rate conditions, this resulted in increased task routinization. Thus, a Schema Theorists could also argue that more neutral trials in faster event rate conditions increased task routinization, which therefore makes the prediction that the vigilance decrement is more severe as event rate gets faster.

**External Motivation Performance Hypotheses**

The MTFR predicts that external motivation will attenuate the vigilance decrement because it is hypothesized that external motivation increases the internal reward that are allocated when the participant responds correctly on a given sustained attention trial. These rewards reduce the likelihood of microlapses occurring over time, and thus attenuate the vigilance decrement by enabling the participant to have enough time to process the stimuli.

It is unclear whether or not Resource theory predicts that increased external motivation will impact the vigilance decrement. One possibility is that external motivation will result in an increased willingness to allocate resources to the task. However, it is unclear whether this will result in an improvement in initial performance on the task, or an attenuation of the vigilance decrement.

The MTF states that effort occurs in sustained attention tasks by reducing the production utility, and thus preventing the likelihood of a microlapses. Thus, MTF makes a nuanced prediction where increased external motivation will result in an attenuation of the vigilance decrement, yet also an increase in false alarms. The MTF predicts an increase in false alarms because due to a lower production utility, other, non-relevant cognitive actions are more likely to be executed.

Schema Theory makes a clear prediction regarding the impact of motivation on sustained attention tasks. Schema Theory posits that attention withdrawing from the task due to task routinization causes the vigilance decrement. Given that external motivation can provide an incentive for increased attention allocation, the theory predicts that there well be less attention being withdrawn from the task, and thus an attenuation of the vigilance decrement in conditions with increased motivation.

**Cognitive Slowing Hypotheses**

Resource Theory and Schema Theory do not make explicit prediction regarding the pattern of slowing that occurs on a given trial of a sustained attention task over time. The reason for this is that these theories are not described at this level of detail. It could be argued that slowing will occur in the processing of a given sustained attention trial, but where and when this slowing occurs is unclear.

The MTF and the MTFR however make explicit predicts on the patterns of slowing that occurs in a sustained attention task. The MTF predicts a similar slowing across the differing event rate conditions because according to MTF, slowing in sustained attention tasks is primarily caused by time-on-task. Since the event rate manipulation does not impact time-on-task, the MTF predicts that a similar rate of slowing will occur over time for each event rate condition.

The MTF also predicts that at each stage of processing a stimulus, slowing will occur at a similar rate. The reason for this is that in previous models that have instantiated

MTF, ACT-R's built in utility learning algorithm was not used. Thus, according to MTF a similar rate of slowing will occur at each stage of processing a given sustained attention trial, which in this study include: (i) the time to look at the first stimulus, (ii) the time between looking at the first stimulus and second stimulus, and (iii) the time between looking at the second stimulus and responding. For similar reasons, MTF also does not predict that motivation will impact the vigilance decrement.

The MTFR predicts that more slowing will occur as event rate gets faster because in faster event rate conditions there is less opportunity to take an opportunistic task break, and thus, more goal-directed-attention-time (GDAT) and more microlapses of attention. Therefore, to support MTFR, as event rate increases the time it takes to perform each of the phases of processing a trial should also increase. In other words, based on MTFR an interaction between event rate and time-on-task is predicted for all three phases of processing, where faster event rate conditions have increased slowing. In order to support the utility learning component of MTFR, cognitive actions that occur earlier in the processing of a stimulus will show more slowing than those that occur later in the processing of a stimulus. The reason that earlier cognitive actions are slower over time is because less reward is propagated to later cognitive actions than more recent cognitive actions in proximity to a reward. Given that participants are sufficiently motivated, MTFR predicts that external motivation will also reduce slowing through a similar process as how internal rewards impact slowing.

**Epworth Sleepiness Scale Survey Hypotheses**

Responses on the Epworth Sleepiness Scale (ESS) (Johns, 1991) are correlated to sleep related processes and the severity of the vigilance decrement (Shaw, Matthews, Warm, Finomore, Silverman, & Costa, 2010). Resource Theorists and Schema Theorists do not make explicit predictions regarding how sleep related processes impact the vigilance decrement. While based on both theories, it can be assumed that increased fatigue will lead to worse performance, the processes by which this decline in performance occurs are unclear.

Both the MTFR and the MTF have an explicit mechanism by which fatigue related processes impact the vigilance decrement, by including a biomathematical model of sleep related processes in these models (McCauley, et al., 2013; Gunzelmann et al., 2009). It is therefore hypothesized by both the MTFR and the MTF that responses on the ESS will be correlated with the vigilance decrement where there will be a steeper vigilance decrement with increased reported sleepiness on the ESS.

**Table 2. Predictions based on the different theories of sustained attention. The four major theories of vigilance are on the y-axis and the different effects are on the x-axis**

| | **Event Rate Performance Hypotheses** | **Motivation Performance Hypotheses** | **Perceptual Processing of a Trial** | **Epworth Sleepiness Scale** |
|---|---|---|---|---|
| **MTFR** | Steeper vigilance decrement with faster event rate | An attenuation of the vigilance decrement with more motivation, but not more false alarms | More slowing for faster event rate conditions<br><br>Less slowing for more motivation<br><br>More slowing earlier in the processing of a stimulus | A correlation between sleepiness and the vigilance decrement |
| **MTF** | No impact of event rate on the vigilance decrement | An attenuation of the vigilance decrement with more motivation, but more false alarms | Similar slowing overtime in all event rate conditions<br><br>No explicit prediction on the impact of motivation<br><br>Similar slowing at each stage of processing a trial | A correlation between sleepiness and the vigilance decrement |
| **Schema Theory** | No explicit predictions regarding event rate | An attenuation of the vigilance decrement with increased motivation | No explicit predictions | No explicit predictions |
| **Resource Theory** | Steeper vigilance decrement with faster event rates | No explicit predictions regarding motivation | No explicit predictions | No explicit predictions |

# CHAPTER TWO: STUDY 1 METHOD

**Participants**

93 George Mason University undergraduate students participated for course credit. Participation was voluntary and cell phones were temporarily removed when performing the task. All participants had normal or corrected to normal vision. Two participants were eliminated because they left the testing room before the experiment ended. One participant was eliminated because of a failure of the experimental software. Another participant was eliminated because responses were made on non-critical trials more than 50% of the time, indicated that the participant was responding sporadically and not properly engaged in the task.

Five additional participants were eliminated from inclusion in the study because of poor practice performance, as is a convention in the sustained attention literature (Hitchcock et al., 1999; Grier, Warm, Dember, Matthew, Galinsky, Szalma, Parasuraman, 2003). The average performance on critical trials for the final practice session was 76% accuracy on critical trials, with a standard deviation of 20%. In order to remain in the study, participants were required to detect at least 50% of all critical signals that appeared in the final practice session. Participants with poor practice performance were eliminated to ensure that participants included in the sample could adequately perform the task. In total, 84 participants had their performance data analyzed.

The sample of 84 participants included 59 females and 25 males. The average age of participants was 20.01 years old with a standard deviation of 2.59 years.

While performance data was analyzed for all 84 participants included in the study, eye data for ten of the 84 participants were eliminated because the participants had no fixations on more than 50% of trials in a block – resulting in unreliable data. In total, 74 participants had their eye data analyzed.

Additionally, trials were eliminated from the eye data analysis if there were no fixations for that trial. Eliminating trials based on no eye fixations caused <5% of the trials to be excluded from the eye data analysis.

**Materials**

The sustained attention task was modeled after the clock-face paradigm used by Hitchcock et al. (1999). This task was chosen because it is a frequently used sustained attention task that is highly perceptual, which enabled for the ability to modify the task to elicit eye movements. Instructions were provided to participants using E-Prime experiment software (E-Prime, 2012). The instructions told participants that they were to take on the role of a factory worker, where different combinations of letters, “p” letters and “d” letters represented different materials being produced by the factory. When the factory produced two different materials, represented by the two different letters that appeared on the screen, this represented a critical signal, requiring the participant to press the <SPACEBAR> key in order to prevent the error. If the letters were the same, this represented a non-critical signal and no response was required (see Figure 5).

The letters were presented on a white screen and were located at 1 of 12 clock-face locations, with the restriction that both stimuli were on opposite sides of the clock-face.

For example, if a “p” was at clock-face location one then a “d” could be at clock-face location four, five, six, seven, and eight, but it could not be at the other clock-face locations. Stimuli randomly varied in their location along the clock face, ranging from both stimuli being apart from one another at a distance of 17.26° of visual angle to 25.87° of visual angle. The stimuli order was randomized for each participant with the restriction that two critical signals could not appear one after the next.

The stimuli were chosen in order to reliably categorize fixations and to determine how perceptual processes unfurled over the course of performing a sustained attention trial. This was accomplished by designing the stimuli such that the participant was required to look at both letters in order to make a judgment. This was also accomplished by making the stimuli small and far apart in order to separate and distinguish eye movement.

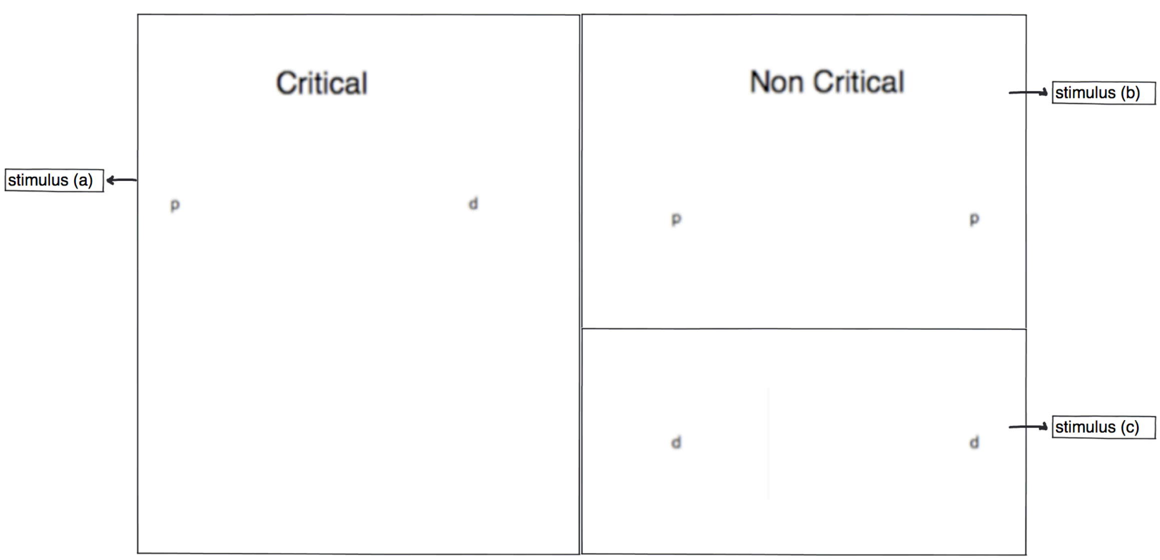


**Figure 5. Experiment Stimuli Illustration. Stimuli presentation examples of critical and non-critical trials. Stimulus (a), the left image, represents a critical trial. Stimulus (b) and stimulus (c), the two right images, represent neutral trials. The participant is required to respond when the letters are different. The above images are not drawn to scale and not all of the letter locations are represented.**

Each trial began with two letters being presented simultaneously for 500 ms. This was followed by a mask. The mask was present for 150 ms. For the remaining trial duration, a fixation cross appeared. The duration of the fixation cross was dependent on the condition that was run. In the fast event rate condition, the duration of the fixation cross was 950 ms, in the medium event rate condition it was 1,750 ms, and in the slow event rate condition it was 2,550 ms (see Figure 6). This resulted in 1500 trials in the fast event rate condition, 1000 trials in the medium event rate condition, and 750 trials in the slow event rate condition.

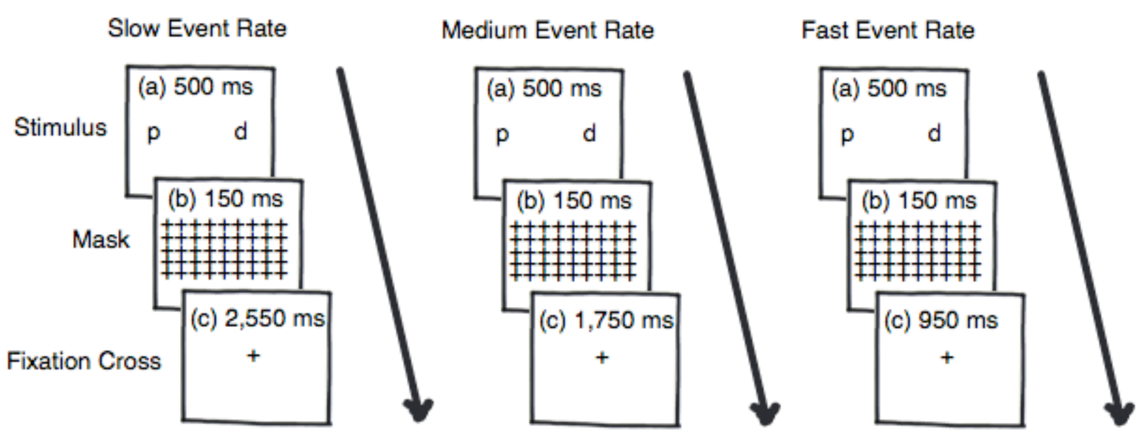



**Figure 6. Experiment Trial Illustration. An illustration of how each trial progresses in the three event rate conditions. In all three conditions, the stimuli are presented for 500 ms and a mask is presented for 150 ms. A fixation cross then appears for**

**2,550 ms in the slow event rate condition, 1,750 ms in the medium event rate condition, and 950 ms in the fast event rate condition.**

There was a critical signal on 8% of the trials in all three conditions. The percentage of critical trials was identical in order to control for the potential confound of probability matching, as is the convention for vigilance studies where event rate is manipulated (Loeb & Binford, 1968; Lanzetta, et al., 1987). Each condition consisted of trials that lasted for 40 minutes, resulting in 120 critical trials in the fast event rate condition, 80 critical trials in the medium event rate condition, and 60 critical trials in the slow event rate condition.

The ESS was administered to participants in order to evaluate the current subjective daytime sleepiness. The survey included eight questions. In each question the participant was presented with a situation and asked to indicate if there was no chance of dozing, a slight chance of dozing, a moderate chance of dozing, or a high chance of dozing, for the given situation. The eight situations included: 1) Sitting and reading, 2) Watching TV, 3) Sitting inactive in a public place, 4) Being a passenger in a car for an hour without a break, 5) Lying down to rest in the afternoon when circumstances permit, 6) Sitting and talking to someone, 7) Sitting quietly after a lunch without alcohol, and 8) Being in a car while stopped for a few minutes in traffic.

**Design**

Participants were randomly assigned to one of the three event rate conditions in a between groups design: fast event rate (a trial was presented every 1600 ms), medium event rate (a trial was presented every 2400 ms), and slow event rate (a trial was presented every 3200 ms).

**Procedure**

The participants were randomly assigned to one of the three event rate conditions. When the participant came into the lab, they were told that they would be taking on the role of a factory worker and seated approximately 66 cm from the computer monitor. They were then calibrated on an SMI eye tracker. Instructions were given to participants on how to complete the task, followed by ten-minutes of practice, which included two blocks of trials that were each five minutes in length. The two five-minute practice sessions were identical to the condition that participants were assigned with the exception that participants received auditory feedback on the practice when responding.

After the practice was completed, the participant was asked questions about their demographics, including their age, handedness, gender, and ethnicity. The participant was also instructed to complete the ESS (Johns, 1991) in order to evaluate daytime sleepiness. A paper version of the ESS was administered to participants and the experimenter recorded the responses.

The participants were again provided instructions on how to perform the sustained attention task. The experimenter asked the participant if they had any further questions. Their cell phones were taken away and the experimenter left the room. Then the participant performed the 40-minute sustained attention task. When the task was finished the participant was alerted and told to leave the room and get the experimenter. The experimenter then debriefed the participant about the purpose of the study.

**Measures**

Keystroke data were collected for each participant in order to evaluate responses to the sustained attention task. Eye track data were collected using an SMI eye tracker operating at 500hz. A fixation was defined using the dispersion-based eye fixation method, when eye movements fell in a 50-pixel radius of the screen for 30 ms or more. Several areas of interest were defined to analyze the eye track data, including the letter stimuli that were presented on the screen.

# CHAPTER THREE: STUDY 1 RESULTS AND DISCUSSION

## Data Preparation

## Measuring Performance

The vigilance decrement is typically indexed by declines in the percentage of correctly detected signals, though signal detection measures, such as A' prime are also used (Helton, Warm, Tripp, Matthews, Parasuraman, & Hancock, 2010; Davies & Parasuraman, 1982; See et al., 1995). Signal detection measures have the advantage of providing a single measure of performance that takes into account responses to both critical trials and neutral trials. Yet if different mechanisms impact hits and false alarms, this can result in difficulties interpreting signal detection measures (Gartenberg, et al., 2015). Therefore, performance was evaluated by calculating responses to critical trials and neutral trials, independently.

Another convention of the sustained attention literature is to use a response cutoff when analyzing critical trials, whereby if the participant responds to a critical trial after a specified time threshold, such as 1500 ms, it is counted as a miss (Dember, et al., 1999; Hitchcock et al., 2003; Szalma, et al., 2006). However recent evidence suggests that these later responses in time may be valid responses, given the slowing that occurs when performing a sustained attention task (Gartenberg, et al., 2015). Therefore, all responses to critical signals were considered as correct responses.

### Scoring the Epworth Sleepiness Scale

Each answer on the ESS was converted into a value from zero to three where 0 = No chance of dozing, 1 = Slight chance of dozing, 2 = Moderate chance of dozing, and 3 = High chance of dozing. A summation of the converted values for the answers was used to evaluate the participant's score.

## Analysis Approach

### The Time-on-task Variable in Statistical Models

An ANOVA is typically used to evaluate performance on sustained attention tasks. When running an ANOVA, block is typically included as a categorical variable. However, as described by Gartenberg et al. (2015), this provides inaccurate degrees of freedom. Additionally, including block as a categorical variable in an ANOVA results in an issue where improvements in performance over time on the vigil can contribute to statistical differences on the effect of block. Yet the vigilance decrement is characterized by decreases in performance over time, not increases. Instead of including block as a categorical variable, instead, it ought to be included as an interval variable (*i.e.,* a covariate) since it is a proxy variable for time-on-task and time is an interval variable.

Including block as a covariate addresses a major analysis issue when analyzing vigilance data (Gartenberg et al., 2015). Yet even when block is included as a covariate, it is still functioning as a proxy variable for time. When block is used instead of time, the granularity of the variable is lost. This binning that occurs when block is used instead of time results in losing valuable information about the data.

A mixed effects model can address the issue of losing information about the variable of time-on-task when block is used as a proxy variable for time. Mixed effects models are useful for longitudinal data when there are multiple measurements per subject, such as is the case with time-on-task. Using a model mixed effects model, the time that the trial occurred can be used instead of block.

### Evaluating Mixed Effects Models for Parsimony

When developing mixed effects models, it is conventional to include the variables in the model one at a time (Rosnow & Rosenthal, 1996). This is to ensure that the model is not over fitting the data. Over fitting the data can occur when a simpler model does a better job fitting the data than a more complex model, given the model fit and the residual error. If a simpler model provides similar fits to a more complex model that has a higher residual error, then the simple model is sufficient to explain the data. In these cases, the simple model ought to be used instead of the more complicated model.

### A Mixed Effects Model of the Vigilance Decrement for the Event Rate Manipulation

A generalized mixed-effects model with a binomial error distribution (Baayen, Davidson, & Bates, 2008), was used to assess whether faster event rates induced worse performance on critical trials over time. A mixed effects model can account for both random and fixed effects, such that subject variance is better accounted for than it is for regression models. This is important for sustained attention tasks since there is frequently a great deal of subject variance in these tasks (see Figure 7). The model was run in multiple steps in order to evaluate the model for parsimony, and to ensure that a simpler model did not do an equivalent or better job at fitting the data than a more complicated model (see Appendix A).

The mixed effects model that best fit the data was a model that included event rate and time-on-task as a fixed factor and subject as a random factor with the slope for time-on-task allowed to vary for each participant. For this model, the percentage correct on critical trials declined as the task progressed ($z$ = -6.13, $p$ < .05), there was no effect of event rate ($z$ = 1.57, $p$ = .12), and there was an interaction between time-on-task and event rate ($z$ = 4.24, $p$ < .05). The interaction effect was characterized by a steeper decline in critical trial accuracy as the event rate speed increased. In other words, there was a steeper vigilance decrement in faster event rate conditions (see Figure 8 and Table 3). As is the convention in the literature, the data are displayed by block instead of time.

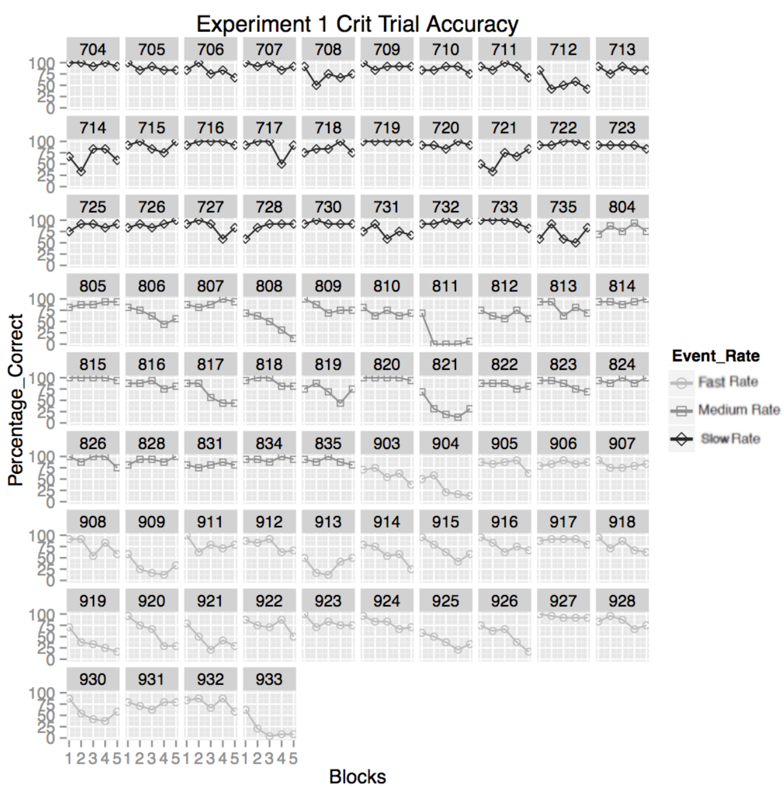


**Figure 7. Experiment 1 individual's critical trial accuracy. Each participant's data is plotted individually. Accuracy on critical trials is on the y-axis and block is on the x-axis. Each block was eight minutes long. Accuracy on the three event rate conditions is plotted.**

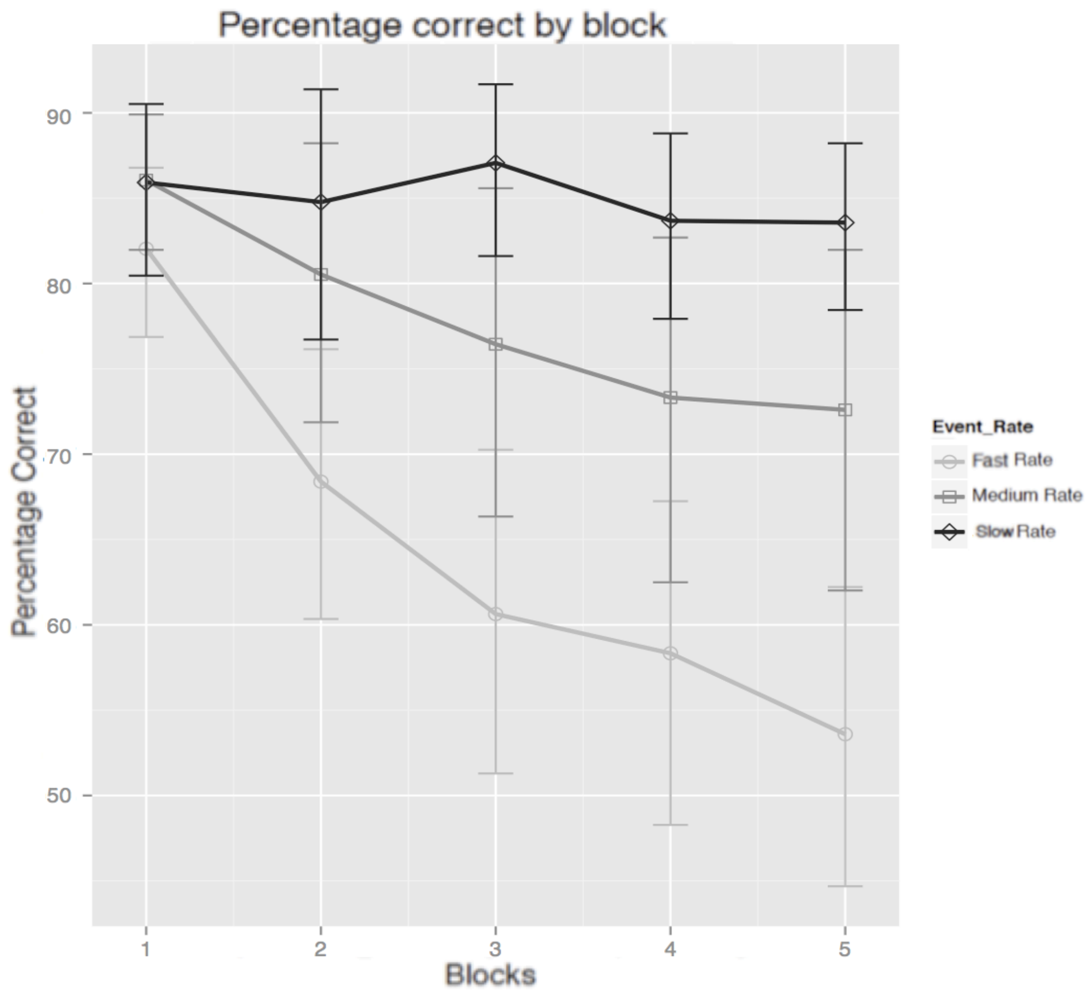



**Figure 8. Experiment 1 Critical Trial Accuracy. Percentage correct for critical trials is on the y-axis and block is on the x-axis. Each block was eight minutes long.. Error bars are 95% confidence intervals.**

The interaction between event rate and time-on-task was consistent with the MTFR and Resource Theory. The MTFR predicts this interaction because in slower event rate conditions, participants can replenish more resources by taking more opportunistic task breaks in slower event rate conditions. This is similar to the "task contingent time-outs" described by Mark, Warm, and Huston (1987). By replenishing more resources during these task breaks, participants experience fewer micro-lapses of attention in the slower event rate conditions. Thus, in the slower event rate conditions, participants are more likely to be able to process and respond to the necessary information in order to make a correct response. Resource theory predicts this interaction because according to Resource Theory, when stimuli appear less frequently, such as is the case with slower event rates, less attentional resources are required to perform the task (Loeb & Binford, 1968; Lanzetta, et al., 1987; Davies & Parasuraman, 1982).

The interaction between event rate and time-on-task is inconsistent with the MTF because the MTF decrements resources based on time-on-task. It is unclear whether or not these results support Schema Theory because it is unclear if equating the event rate conditions based on the number of neutral and critical trials would also results in an interaction between event rate and time-on-task. If the interaction persists under these differing experimental conditions, this would go against Schema Theory.

**Table 3. Experiment 1 critical trial accuracy. Mean critical trial accuracy across blocks for the three event rate conditions. The items in parentheses are standard deviations.**

| | **Fast Event Rate** | **Medium Event Rate** | **Slow Event Rate** |
|---|---|---|---|
| **Block 1** | 82.04% (14.82%) | 86.06% (10.50%) | 85.92% (13.57%) |
| **Block 2** | 68.39% (21.75%) | 80.53% (22.31%) | 84.77% (18.80%) |
| **Block 3** | 60.63% (26.86%) | 76.44% (25.21%) | 87.07% (13.47%) |
| **Block 4** | 58.33% (26.40%) | 73.32% (27.81%) | 83.67% (15.22%) |
| **Block 5** | 53.59% (24.52%) | 72.60% (25.32%) | 83.57% (13.64%) |

**Experiment 1 Mixed Effects Models of Neutral Trials**

The mixed effects model that was used for critical trials was then applied to neutral trials. No effect of time-on-task was found on the percentage correct for neutral trials ($z = 0.39$, $p = .70$), yet a main effect of event rate was found ($z = -2.55$, $p < .05$), where participants had better performance on the percentage correct of neutral trials as event rate got faster. There was no interaction between time-on-task and event rate ($z = 0.32$, $p = .75$) (see Table 4).

Resource Theory and Schema Theory cannot provide a good explanation as to why the percentage correct on neutral trials was better as event rate got faster. However, the MTF and the MTF are instantiated within ACT-R, and ACT-R can provide an explanation for this unexpected finding. In ACT-R, noise is associated with cognitive actions, or productions. Therefore, when ACT-R processes a given trial the likelihood that a cognitive action will randomly rise above the production utility threshold increases with longer trial durations. Therefore, since slower event rate conditions have a longer trial duration, ACT-R predicts that there is a greater opportunity for a response to occur.

**Table 4. Experiment 1 neutral trial accuracy. Mean neutral trial accuracy across block for the three event rate conditions. The items in parentheses are standard deviations.**

| | **Fast Event Rate** | **Medium Event Rate** | **Slow Event Rate** |
|---|---|---|---|
| **Block 1** | 97.09% (4.12%) | 98.08% (2.72%) | 95.25% (4.14%) |
| **Block 2** | 95.93% (7.26%) | 97.68% (3.20%) | 95.50% (4.38%) |
| **Block 3** | 96.35% (4.50%) | 98.04% (2.91%) | 95.40% (4.25%) |
| **Block 4** | 96.28% (6.20%) | 97.83% (2.86%) | 96.32% (4.09%) |
| **Block 5** | 96.63% (4.66%) | 97.47% (3.66%) | 95.70% (5.59%) |

**Eye Movement Analyses For the Event Rate Manipulation**

Eye movement data was used to explore the hypotheses regarding the pattern of slowing when processing a sustained attention trial, and how that processing unfolded over the time-course of the task. Each trial was separated into three segments of time: (a) The amount of time that it took to look at the first stimulus, (b) The amount of time between looking at the first stimulus and the second stimulus, and (c) The amount of time between looking at the second stimulus and responding. All trials were included in the analysis for the amount of time that it took to look at the first stimulus and the amount of time between looking at the first stimulus and the second stimulus. However, only critical trials were included for the analysis on the amount of time between looking at the second stimulus and responding.

A similar mixed effects model was run on the perceptual data as the model for the performance data. In this model, event rate and time-on-task were fixed factors and subject was a random factor with the slope for time-on-task allowed to vary for each participant. Unlike the previous mixed effects models, a Gaussian error distribution was used instead of a binomial error distribution because the dependent variable was an interval variable instead of a binomial variable.

**Stage One of Processing**

For the stage of processing that involved the time it took to look at the first stimulus, participants were slower to look at the first stimulus as time progressed, ($t(69.57) = 4.34$, $p < .05$). Participants were slower to look at the first stimulus in slower event rate conditions, ($t(72.25) = 2.50$, $p < .05$). Consistent with the hypothesis that was based on the MTFR, there was an interaction between time and event rate, ($t(73.30) = -2.55$, $p < .05$), where in faster event rate conditions, participants were increasingly more slow at processing the first stimulus over time (see Figure 9).

To examine the nature of this interaction, post-hoc comparisons were conducted using the mixed effects model by comparing the slow event rate condition with the medium event rate condition, the medium event rate condition with the fast event rate condition, and the slow event rate condition with the fast event rate condition. No interaction effect was found when comparing the slow event rate condition to the medium event rate condition $t(44.29) = -0.84$, $p = .41$, and no interaction was found between the medium event rate condition and the fast event rate condition, ($t(46.42) = -1.53$, $p = .13$). However, a significant interaction was found between the slow event rate condition and the fast event rate condition, ($t(52.36) = -2.46$, $p < .05$), where for faster event rate conditions, participants were increasingly more slow over time.

While Resource Theory and Schema Theory do not make any explicit predictions regarding the pattern of slowing that occurs in sustained attention, recall that the MTF posits a similar slowing between the event rate conditions. The MTF posits a similar slowing between event rate conditions over time because according to the MTF, microlapses are induced based on time-on-task. The MTFR was supported by the finding that there was an interaction between event rate and time-on-task, and that this interaction was driven by differences between the slow event rate and fast event rate conditions. The MTFR hypothesizes this interaction because participants have more time to take opportunistic task breaks that reduce the likelihood of a microlapse when in the slower event rate condition. The result of fewer microlapses in slower event rate conditions is less slowing over time in the slow event rate condition than the faster event rate condition.

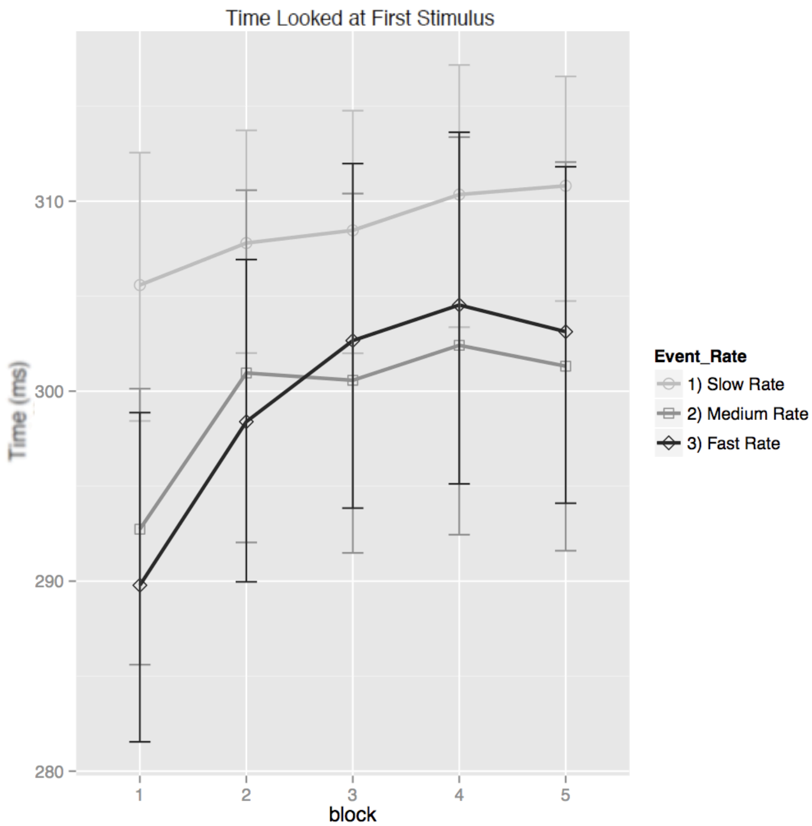



**Figure 9. Experiment 1 time to look at first stimulus. Time in milliseconds is on the y-axis, block is on the x-axis, and the different event rate conditions are compared for how long it took participants to look at the first stimulus.**

**Stage Two of Processing**

The next stage of processing the stimuli was the time between looking at the first stimulus and the second stimulus. There was no effect of event rate, ($t(71.88) = 0.14$, $p = .89$). There was a marginal main effect of time-on-task where participants were increasingly faster as time-on-task preogressed, ($t(69.15) = 1.78$, $p = .08$). An interaction between event rate and time-on-task was found where participants were increasingly slower over time as event rate got faster, ($t(71.79) = -2.05$, $p < .05$). (see Figure 10).

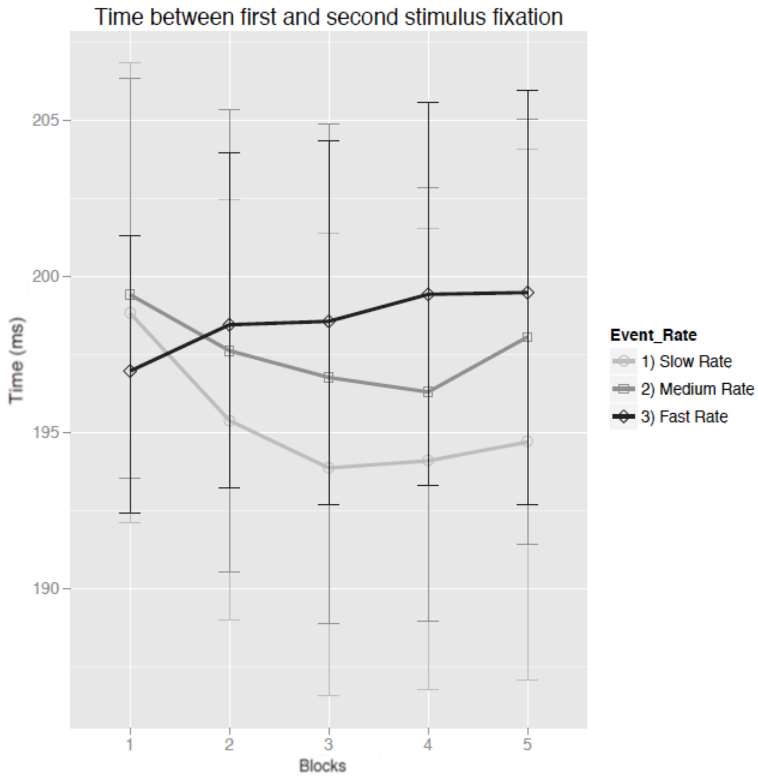



**Figure 10. Experiment 1 time between looking at the first and second stimulus. Time in milliseconds is on the y-axis, block is on the x-axis, and the different event rate conditions are compared for the time between how long it took participants to look at the first stimulus and the second stimulus.**

Similar to the first stage of processing, post-hoc comparisons were again used to examine this interaction. No interaction effect was found when comparing the slow event rate condition to the medium event rate condition ($t(43.99) = -0.82$, $p = .41$), and no interaction was found between the medium event rate condition and the fast event rate condition, ($t(45.09) = -1.14$, $p = .26$). However, a marginal interaction was found between the slow event rate condition and the fast event rate condition, ($t(51.15) = -1.92$,

$p = .06$), whereby, participants were increasingly more slow over time in the slower event rates. These findings suggest that differences between each of the three conditions contributed to produce the interaction between event rate and time-on-task where as event rate was faster, more slowing occurred over time.

The interaction between event rate and time-on-task again supported the MTFR and was counter to the MTF. This interaction however is quite different than the results from the first stage of processing, when all the event rate conditions got slower over the course of time. Yet for the second stage of processing, participants only slowed for the fast event rate condition and got faster for the slow event rate condition.

Recall that the MTFR also predicts that more slowing will occur earlier in processing than later in processing due to the proximity of rewards that occur when performing a sustained attention trial. In order to explore the differences between the stages of processing, a stage of processing variable was added to the mixed effects model as a fixed factor and the first stage of processing was compared to the second stage of processing.

There was more slowing over time, ($t(333) = 4.70$, $p < .05$), more slowing in faster event rate conditions, ($t(120) = 6.51$, $p < .05$), and participants were slower in earlier stages of processing, ($t(135648) = -42.88$, $p < .05$). There was no interaction between time-on-task and event rate, ($t(406) = -1.25$, $p = .21$), and there was no three-way interaction between time-on-task, event rate, and stage of processing, ($t(135655) = -1.19$, $p = .24$). However, there was an interaction between time-on-task and stage of processing, ($t(135666) = -2.25$, $p < .05$), where participants were slower to look at the stimulus over time in the first stage of processing than the second stage of processing. Additionally, there was an interaction between event rate and stage of processing, ($t(135642) = -9.90$, $p < .05$), where participants were slower to look at the stimulus for faster event rate conditions in the first stage of processing than the second stage of processing.

Unlike MTF, the MTFR posits that more slowing occurs in earlier stages of processing due to the impact that utility learning has on microlapses. The MTFR postulates that a small internal reward occurs when the participant successfully processes both stimuli – the cognitive action that is necessary in order to successfully respond to a trial. The interaction between stage of processing and time-on-task provided support for this component of MTFR because more slowing occurred over time in the first stage of processing than the second phase of processing that involved successfully looking at both stimuli.

None of the other theories of sustained attention postulate this interaction. The MTF posits a similar rate of slowing for each of the stages of processing. While Resource Theory and Schema Theory do not make predictions at this level of detail regarding how long it takes to process stimuli within a given trial.

In the slow event rate condition, participants looked at the stimulus more quickly as time-on-task increased, an unexpected finding. One explanation for this finding is that when participants look at the second stimulus, other cognitive mechanisms such as learning, can over-ride the impact of microlapses, as was also demonstrated by Parasuraman and Giambra (1991).

Further support for the explanation that learning processes can override the impact of microlapses was based on the task design. More learning was involved in the second stage of processing than the first stage of processing because the spatial location of the second stimulus followed a more predictable pattern than the spatial location of the first stimulus. The first stimulus was more randomly spatially located on the screen because it could be in one of twelve regions. However, the second stimulus had the spatial requirement of being on the opposite side as compared to the first stimulus, so that it could only be in one of six locations.

**Stage Three of Processing**

The third stage of processing regarded the time between looking at the second stimulus and responding. As a result, only critical trials that included a response were included in the analysis. There was no effect of event rate, ($t(68.04) = 1.36$, $p = .18$), and there was no effect of time-on-task, ($t(67.66) = -1.06$, $p = .19$). Recall that MTFR makes the prediction that there will be more slowing over time for faster event rate conditions. However, unexpectedly, there was an interaction between event rate and block, ($t(70.25) = 2.39$, $p < .05$), but this interaction was in the opposite direction as predicted based on MTFR. Over the course of the task participants slowed over time more for the lower event rate condition than the faster event rate condition.

To examine the nature of this interaction, post-hoc comparisons were conducted similar to the comparisons that were made for the previous stages of processing analyses. No interaction effect was found when comparing the slow event rate condition to the medium event rate condition ($t(45.04) = 0.77$, $p = .45$). However, a marginal interaction was found between the medium event rate condition and the fast event rate condition, ($t(47.57) = 1.73$, $p = .09$), and a significant interaction was found between the slow event rate condition and the fast event rate condition, ($t(47.41) = 2.42$, $p < .05$), whereby, participants were increasingly more slow over time in slower event rates.

One explanation for this finding is that participants took strategic breaks in the third stage of processing because they could take advantage of the longer trial durations that occurred in the slower event rate conditions. Because the trial durations were longer in slower event rate conditions, participants may have felt less pressure to respond quickly to the stimuli. Since participants had less pressure to respond when the stimuli appeared at a slower rate, participants may have taken advantage of this by taking additional task breaks in order to replenish resources.

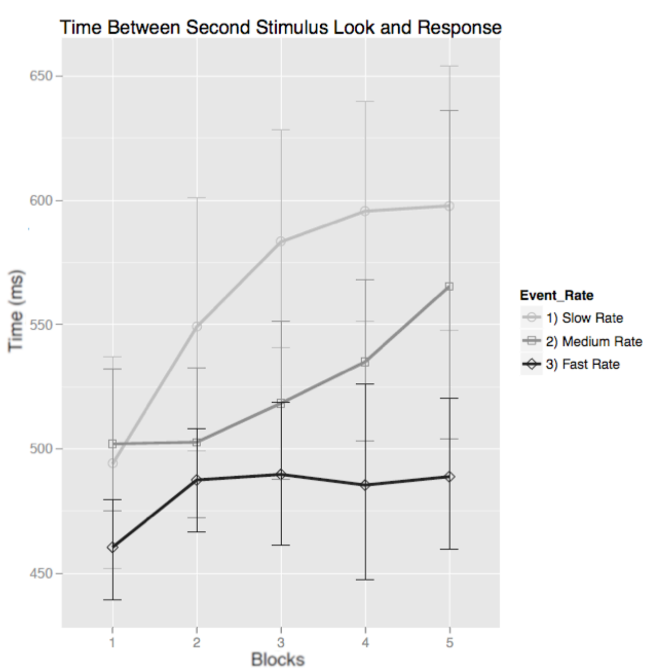


**Figure 11. Experiment 1 time between the second stimulus look and a response. Time in milliseconds is on the y-axis, block is on the x-axis, and the different event rate conditions are compared for the time between how long it took participants to look at the second stimulus and to respond.**

**Not Looking As a Source of Errors**

Based on MTFR it was hypothesized that as event rate increases in speed, more slowing occurs. This cognitive slowing results in PTEs, or errors that occur when the participants does not have enough time to process the stimuli. In order to test the PTE hypothesis, a mixed effects model was run with the percentage of time that both stimuli were fixated on as the dependent variable in the mixed effects model.

There was a main effect of time-on-task, ($t(71.81) = -4.75$, $p < .05$), where participants were increasingly less likely to look at both stimuli as time-on-task increased. There was no main effect of event rate on the likelihood of looking at both stimuli, ($t(72.25) = -0.41$, $p = .68$). In support of the MTFR, there was an interaction between event rate and time-on-task for the mixed effects model, ($t(72.89) = 2.74$, $p < .05$), where participants were increasingly less likely to look at both stimuli in the higher event rate conditions as time-on-task increased (see Figure 10). Also in support of PTEs, when both stimuli were not looked at, participants were more likely to make an error (see Appendix B).

To examine the nature of this interaction, post-hoc comparisons were conducted using the mixed effects model. A marginal interaction effect was found when comparing the slow event rate condition to the medium event rate condition ($t(44.91) = 1.91$, $p = .06$), where in support of MTFR, the medium event rate condition had a steeper decline in the percentage of time that both stimuli were looked at than the slow event rate condition. No interaction was found between the medium event rate condition and the fast event rate condition, ($t(46.11) = 0.96$, $p = .34$). Also in support of MTFR and the concept of PTEs, the fast event rate condition had a steeper decline in the percentage of time that both stimuli were looked at than the slow event rate condition, ($t(51.80) = 2.59$, $p < .05$).

Since participants need to look at both stimuli in order to make a judgment on whether or not to respond, this suggests that not looking at both stimuli may be a major source of errors in sustained attention tasks. This is supported by the similar interaction effect that was previously reported in the vigilance decrement analysis.

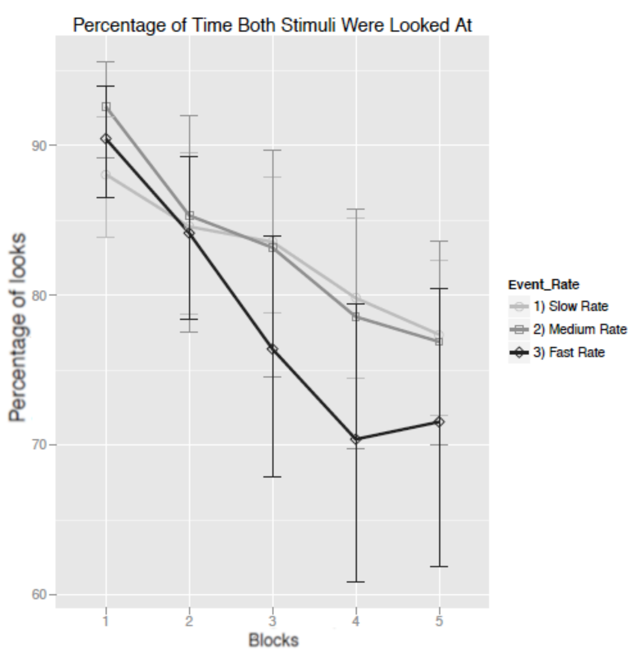



**Figure 12. Experiment 1 percentage of time that both stimuli were looked at. The percentage of time that both stimuli were fixated on is on the y-axis, block is on the**

**x-axis, and the different event rate conditions are compared for the percentage of time that both stimuli were fixated on.**

**Epworth Sleepiness Scale Analysis For the Event Rate Manipulation**

Recall that unlike Schema Theory and Resource theory, the MTF and the MTFR explicitly define sleep related processes based on a biomathematical model of fatigue (McCauley, et al., 2013). Since the ESS has been shown to be sensitive to the components of sleep described by the biomathematical model of fatigue (Johns, 1991), a relationship between performance on ESS and the vigilance decrement is hypothesized by both the MTFR and MTF. A relationship between increased sleepiness on the ESS and a steeper vigilance decrement would also support previous research regarding the individual differences factors that can impact sustained attention performance (Shaw, et al., 2010)

To test this hypothesis, the slope of participant performance on critical trials was calculated. Then, using a Pearson's correlation, it was found that there was a marginal negative correlation between the Epworth and the slope of vigilance task performance, $r(82) = -.20$, $p = .07$, where worse performance over time on critical trials was associated with higher sleepiness scores. While this was below significance, it was a small to moderate effect size in the hypothesized direction.

# CHAPTER FOUR: STUDY 1 DISCUSSION

The performance data and the perceptual data support the process account of the vigilance decrement articulated by the MTFR, where there was a steeper vigilance decrement as the event rate increased and increased slowing was found in faster event rate conditions. This pattern of slowing was consistent with the prediction from MTFR that more slowing occurs in faster event rate conditions due to increased microlapses of attention. Similar to MTFR, MTF predicts that microlapses are the main process by which errors are induced in sustained attention tasks; however, MTF predicts a similar rate of slowing across event rate conditions. These theories differ because according to MTFR, participants take task-contingent breaks that are opportunistic in nature between processing stimuli, whereby, more breaks occur in slower event rate conditions, GDAT decreases, and more replenishment occurs. This causes fewer microlapses and an attenuation of the vigilance decrement.

While Resource Theory predicts this interaction for the vigilance decrement between event rate and time-on-task (Loeb & Binford, 1968; Lanzetta, et al., 1987; Davies & Parasuraman, 1982), it is unclear what prediction Schema Theory makes regarding this interaction. Both Resource Theory and Schema Theory do not make clear predictions regarding the pattern of slowing in sustained attention tasks because unlike the MTF and the MTFR, they do not provide a detailed process level account of the vigilance decrement phenomenon that is explicitly defined by including fatigue related mechanisms in a computational cognitive architecture.

Unexpectedly, for neutral trials, there was no impact of time-on-task false alarms, yet there were more false alarms in slower event rate conditions. The null effect of time-on-task on neutral trials was expected, given that previous studies that manipulated event rate reported inconsistent results for false alarms (Loeb & Binford, 1968; Lanzetta, et al., 1987). However, it was unexpected that more false alarms occurred in slower event rate conditions, and no theory of sustained attention explicitly makes this prediction. However, ACT-R provides an explanation for this finding, whereby, the production, or cognitive action, responsible for responding to the stimulus is relatively more likely to fire when the trial is longer than when it is shorter. This is due to how cognitive actions are implemented in ACT-R and the noise associated with these cognitive actions, where for longer trials, the cognitive action is more likely to randomly be above the threshold.

The pattern of slowing in the perceptual data also supported the internal reward mechanism posited by the MTFR. Over the time-course of the vigil there was more slowing in the first stage of processing than the second stage of processing. Additionally, in the first stage of processing, more slowing occurred over time in all of the event rate conditions. However, in the slow event rate condition the second stage of processing cognitive action was faster over time.

The pattern of slowing in the perceptual data was consistent with the internal reward mechanism posited by the MTFR, given that an internal reward occurs when participants successfully look at both stimuli. Because the cognitive action responsible for looking at both stimuli is necessary for correctly responding to the trial, it was assumed that for this cognitive action, a small internal reward occurs when it was successfully executed. In temporal discount learning, when internal rewards occur, cognitive processes that are closer in time to those rewards get a greater amount of the reward (Sutton & Barto, 1998; Anderson 2007). Due to this temporal discount learning process, the reward component of MTFR predicts that the cognitive action related to looking at the first stimulus gets less of a reward than the cognitive processes that involved looking at the second stimulus. It is therefore posited by the MTFR that increased rewards to a cognitive action result in less slowing over time to that cognitive action. As a result, the theory posits that the first stage of processing is particularly impacted by the depletion of the central cognition resource.

Interestingly, the MTFR is also consistent with the finding that certain stages of processing can get faster over time, particularly those cognitive actions that are closer in proximity to a reward. Therefore, one explanation for why certain tasks with high rewards and decreased GDAT are characterized by improved performance over time is that these replenishment related processes outweigh the impact of increased fatigue related processes. This may provide an explanation as to why certain tasks, such as video game performance, are typically characterized by improved performance over time.

There was also an unexpected findings involving the third stage of processing the stimuli, namely the time between processing the second stimulus and responding. In this third stage of processing, there was an interaction between event rate and time-on-task; however, this interaction was in the opposite direction as predicted. There was more slowing over time in the slower event rate conditions than the faster event rate conditions. One explanation for this finding is that because participants had more time to respond in the slower event rate condition, they opportunistically took advantage of this extra time. This implies that over time, participants needed to take more opportunistic task breaks, but had a greater ability to do so in slower event rate conditions because of the increased time between the trials. While this was not predicted by the MTFR, it is consistent with the hypothesis from MTFR that participants take opportunistic task breaks. However, the finding also suggests that participants may strategically take these breaks even while responding to a stimulus.

It was also found that increased reported sleepiness on the ESS taken prior to the vigil were marginally correlated with a steeper vigilance decrement. Since the ESS is sensitive to the components of sleep and the MTF and the MTFR include these components of sleep in the fatigue component of the models, the marginal correlation supports this aspect of the theories. This finding provides further support for the notion that the process responsible for fatigue effects found in the literature is similar to the process responsible for the vigilance decrement (Veksler & Gunzelmann, *under revision*). While it could be consistent with Resource Theory and Schema Theory that fatigue related processes impact the vigilance decrement, these processes are not explicitly articulated by the theories.

# CHAPTER FIVE: BUILDING A COMPREHENSIVE MODEL OF VIGILANCE

The main goal of this research is to develop a comprehensive computational model of sustained attention that can explain the various effects in the literature across a wide variety of sustained attention tasks. Previous modeling efforts that have employed the MTF have been successful in modeling the vigilance decrement effect (Veksler & Gunzelmann, *under revision*), the signal duration effect (Gartenberg et al., 2014), and the memory effect (Gartenberg et al., *in prep*) by integrating the MTF within the ACT-R cognitive architecture. A similar approach to these previous efforts is taken here.

A computer simulation of the task was developed with the same task parameters that participants experienced in the experiment. This included the 500 ms stimulus presentation, variable trial durations based on the event rate conditions, an identical number of trials for each condition, and presenting the model with “p’s” and “d’s” with 8% of the trials being critical stimuli.

An ACT-R model was developed that could perform the task (see Table 5 and Appendix C). The replenishment mechanisms posited by the MTFR were then applied to the model. A successful model would be able to fit the performance data for both critical and neutral trials and provide an explanation for the pattern of slowing that was found in Experiment 1.

**An ACT-R Model of the Sustained Attention Task**

Recall that central cognition in ACT-R is responsible for the matching, selection, and execution of cognitive actions based on the pattern of information that are in ACT-R's buffers. The information in the buffers is the pieces of information from each module that have the highest activation. Actions are made based on *production rules*, which specify what to do when specific conditions in the buffers are met. For the sustained attention tasks in this paper, Table 5 describes the production rules that were used.

**Table 5. ACT-R model productions. The italicized production names provide a brief description of the function of the productions and the production description provides the If / Then logic of the production in ACT-R.**

| Production Names | Production Descriptions |
|---|---|
| *attend and encode* | **If** a stimulus is present **Then** visually encode the stimulus and look for the next stimulus |
| *store in memory and encode* | **If** the next stimulus is found, **Then** store the first stimulus in memory and visually encode the second stimulus |
| *compare-distracter* | **If** what is visually encoded is the same as what is in memory **Then** do nothing |
| *compare-target* | **If** what is visually encoded is different **Then** press the space bar |
| *respond* | **If** the goal is to do the task **Then** press the space bar |
| *break* | **If** no stimuli are currently being processed **Then** take a break |

The model began the trial with the *attend and encode* production. This cognitive action, or production, was responsible for visually attending to the information on the simulated computer screen (*i.e.,* a letter "p" or a letter "d"). When it was detected that the information was present, a request was then to visually encode the information and move attention to the next stimulus (*i.e.,* the letter "p"). If the next stimulus was found, then the *store in memory and encode* production was fired. This production stored the first stimulus in ACT-R's *imaginal buffer* and encoded the second stimulus. The *imaginal buffer* in ACT-R is used for representations of the task problem state. Finally, either the *compare-distracter* production or the *compare-target* production fired based on what was in the model's imaginal buffer and visual buffer. If the information in the imaginal buffer and visual buffer were identical, this indicated that no response was required. This triggered the *compare-distracter* production to fire and no response was made. If the information in the imaginal buffer and the visual buffer were different, this indicated that a response was required and the *compare-target* production was fired, which triggered the model to respond and press the spacebar.

Additionally, a *respond* production was implemented in order to simulate the process of responding to a stimulus without having to necessarily process the stimulus. This enabled for false alarms to be explored. In order to ensure that this production did not always fire, the production utility was set to .4. This production may also be used to simulate higher level processes, such as probability matching, which have been shown to be used in sustained attention tasks that manipulate the percentage of critical trials (Gartenberg et al., *in prep*).

**Modeling the Sustained Attention Task Using the MTFR**

The MTFR modifies the MTF by proposing that a different factor than time-on-task impacts production utilities. The MTFR differentiates between when attention is directed towards the task (time-on-task) and when it is not directed on the task (time-off-task). The model differentiates between time-on-task and time-off-task with the addition of a *task break production*, which fires when no stimuli are perceived on the screen and no stimuli are being processed.

The MTFR replaces the time-on-task variable described in the MTF (see Equation 1) with the GDAT variable and eliminates the fp-percent variable (see Equation 2). To calculate GDAT, the total accumulated time-on-task and time-off-task is used (see Equation 3). Since trials are longer in the slower event rate conditions, participants in the slower event rate conditions have more time-off-task. As a result, the decrement is attenuated in slower event rate conditions, as compared to faster event rate conditions. The Equation 2 instantiation of fp makes it possible to eliminate the FP-percent parameter because time-off-task can be used to "wake up" the model when production utilities are low.

$$fp = fp\text{-}percent * (1 + time\text{-}on\text{-}task)^{fpmc}$$

**Equation 1. MTF simplified FP utility scalar function. FP is the scalar used to induce microlapses by impacting the utility function. Fpmc is the time-on-task slope for the production utility. FP-percent represents the accumulated effect of microlapses on production utility.**

$$fp = (1 + gdat)^{fpmc}$$

**Equation 2. MTFR modified FP utility scalar function. FP is the scalar used to induce microlapses by impacting the utility function. Fpmc is the gdat slope for the production utility.**

$$GDAT = \text{time-on-task} - (\text{time-off-task} * \text{rpmc})$$

**Equation 3. Goal-directed-attention-time (GDAT) equation. Rpmc is a parameter relating the time-off-task exponent to the production utility.**

The time-off-task replenishment mechanism also provides an explanation as to why certain tasks induce a vigilance decrement, while other tasks do not. If the task-based features permit the participant to take small rests while processing stimuli, this can attenuate the vigilance decrement. This mechanism can also explain stimuli presentation uncertainty effects reported in the literature (Scerbo et al., 1987), where stimuli that are presented at unpredictable times induce a more severe vigilance decrement. The explanation for this effect, based on MTFR, is that when stimuli are not presented at regular intervals, rest periods cannot be predicted, so GDAT increases, where attention is required at a more continuous rate.

Recall that the other replenishment mechanism posited by MTFR is that internal rewards impact which cognitive actions have the most slowing when performing a sustained attention task. Included in ACT-R is a built in reward mechanism for learning called utility learning, which is based on the well-established temporal difference learning algorithm (Sutton & Barto, 1998). For utility learning, tasks are learned based on the proximity of cognitive actions to a reward (Anderson, 2007). Since learning processes have been shown to be involved in even simple tasks, such as sustained attention tasks (Parasuraman & Giambra, 1991), MTFR posits that this built in component of ACT-R should be used when modeling sustained attention tasks. It was assumed that participants receive a small internal reward every time that they look at both stimuli, since this was the essential cognitive action necessary to perform the task accurately.

A parameter search was conducted to find the best fitting parameters for the theoretical components of the model using mindmodeling.org (Harris, 2008). The best fitting value were -0.07 for fpmc, 2.12 for rpmc, and 1.96 for the initial utility. A reward of 3.5 was given to the model each time both stimuli were fixated. The model was run 100 times in each condition.

The model produced good fits to the human performance data ($R^2$ = 0.95, *RMSE* = 2.15%) (see Figure 16). Importantly, there was a steeper vigilance decrement as event rate got faster. The MTF did not make this prediction (see Appendix C), but the MTFR made this prediction because of the process in MTFR of GDAT whereby opportunistic breaks occur when attention is not necessary for the successful performance of the sustained attention task.

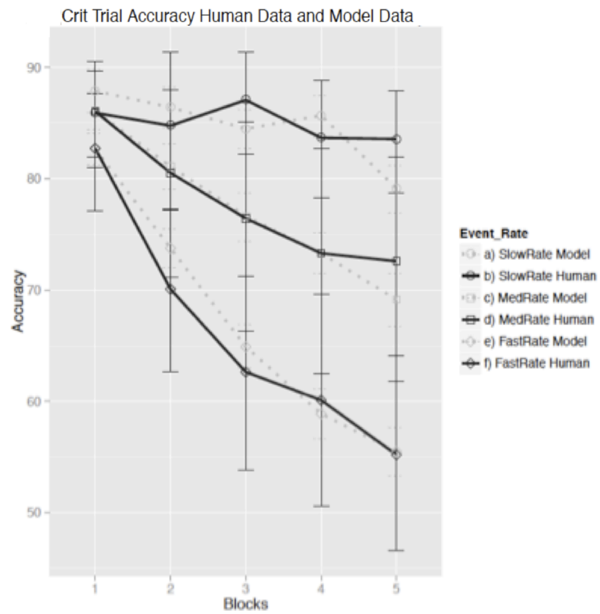



**Figure 13. MTFR model fit of the vigilance decrement. Human performance accuracy on critical trials compared to the ACT-R model using a version of ACT-R that includes the fatigue component of the MTFR and the reward component of the MTFR.**

Recall the finding for neutral trial performance where there was no time-on-task effect, suggesting that fatigue mechanisms did not impact false alarms. Since fatigue did not impact false alarms, this aspect of the data could be modeled without the fatigue mechanisms included in MTFR. With ACT-R alone, this effect can be modeled by adding an additional production that involved responding at anytime throughout the processing of a trial (the *respond* production). The MTFR posits that such a production is representative of a higher-level processes involved in sustained attention tasks. For example, as was demonstrated by Gartenberg et al., (*in prep*), the *respond* production may represent the process of probability matching, where the participant anticipates the percentage of time that critical trials appear, and thus responds accordingly.

The model produced this effect where there were more false alarms over time in the slower event rate conditions.  The $R^2$ value of .11% is poor, largely due to the fast that the data are relatively flat over time. Additionally, unlike the model where there were more false alarms overall in the slow event rate condition than the medium event rate condition, and more false alarms overall in the medium event rate condition than the fast event rate condition, due to variability in the subject data, there was no difference between the fast and slow event rate conditions, yet fewer false alarms over all in the medium event rate condition.  The RMSE of only 1.33% demonstrated a relatively close fit to the data (see Figure 17).   Importantly, the main effect of event rate was reproduced.

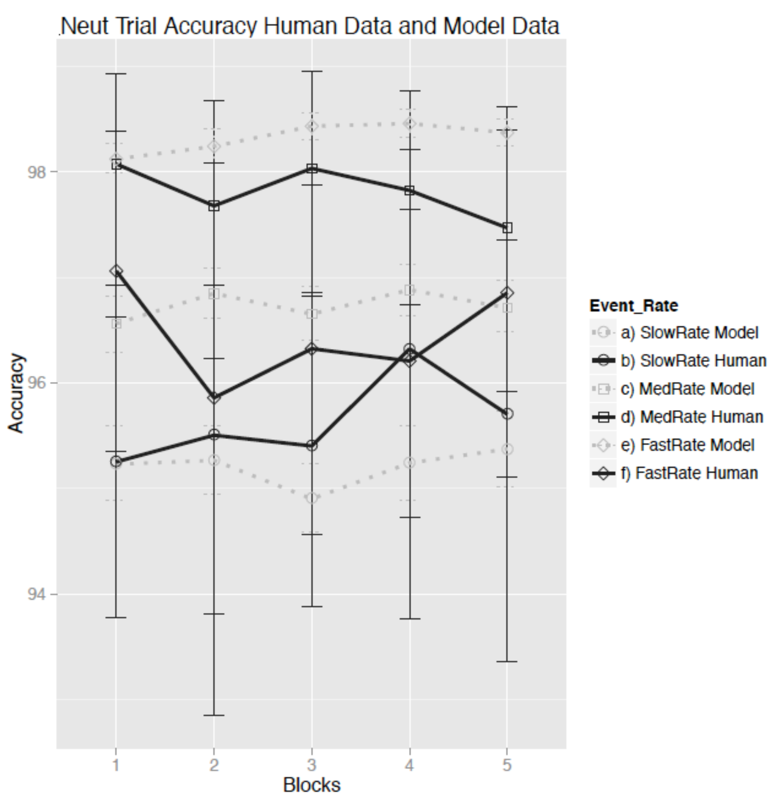


**Figure 14. MTFR model fit of neutral trials. Human performance accuracy on neutral trials compared to the MTFR.**

By analyzing the timing of when productions occur, the processing time of cognitive actions in the model can be determined. This can then be compared against the human perceptual data in order to determine if the same general findings occurred in both the model. Similar to the human data, in the model more slowing occurred in faster event rate conditions due to the GDAT process. Also for the model, more slowing occurred earlier in the processing of a stimulus than later in the processing of a stimulus. Additionally, the model simulated the learning effect demonstrated in the second stage of processing where for the slow event rate condition, the model got faster over time. Under these conditions, the replenishment mechanisms of taking more opportunistic breaks in the slower event rate condition and the internal reward that is closer in proximity to the second stage of processing can outweigh the impact that the MTFR's microlapse process has an the timing of processing stimuli (see Figure 15).

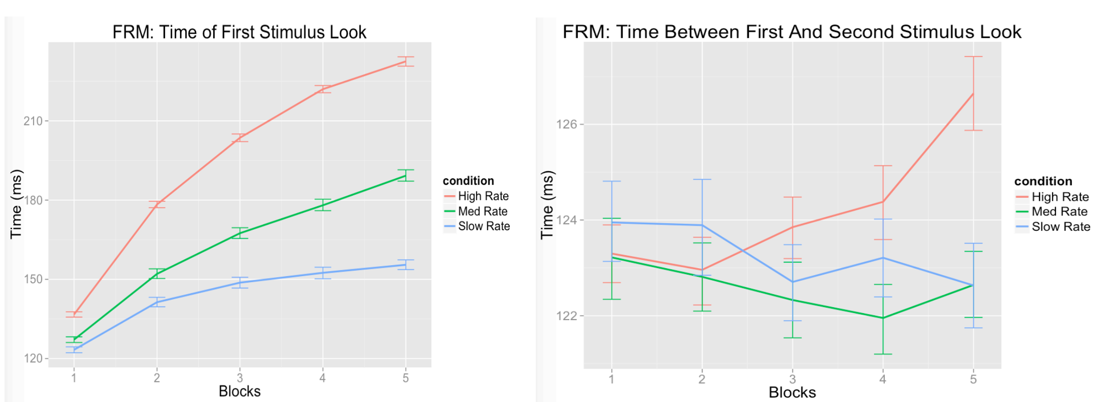


**Figure 15. Model data of when the first and second stimuli are looked at. The left graph shows the time that it took the MTFR model to look at the first stimulus over time and across the three event rate conditions. The right graph shows the time that it took the MTFR model to look at the second stimulus over time and across the three event rate conditions.**

In conclusion, this modeling effort demonstrated that in order to fit the human data from Experiment 1, it was necessary for a model to have two replenishment mechanisms, which included a task break component and an internal reward component. This supported the MTFR over the MTF. How ACT-R processes information was able to explain the false alarm effect because the *response* cognitive action was more likely to occur when trial durations were longer. The model also produced the effects found in the human perceptual data regarding slowing over time, more slowing in faster event rate conditions, more slowing earlier in processing, and the potential for cognitive actions to get faster over time due to learning related processes and increased rest periods.

# CHAPTER SIX: STUDY 2 INTRODUCTION

The finding that internal rewards impact the vigilance decrement suggests that external rewards may also be a useful replenishment mechanism and tool in applied settings for addressing the vigilance decrement. In previous research, it was found that monetary incentives alleviated the vigilance decrement when performing a sustained attention task when sleep deprived (Horne, et al., 1985). Furthermore, it was found that simply by informing participants that they are being monitored resulted in the alleviation of the vigilance decrement (Bonnefond, et al., 2011). These findings are in support of the hypothesis that external rewards impact the vigilance decrement,

The hypothesis that external rewards impact the vigilance decrement is also consistent with the MTFR. Because when utility learning is used in MTFR, cognitive actions receive internal rewards when both stimuli are successfully looked at. The model proposes that the reward received when both stimuli are fixated on increases in conditions where there is a greater external reward. The result of an increased reward value is that the task related cognitive actions are more likely to fire and microlapses are less likely to occur.

## Study 2 Hypotheses

In Experiment 2, external rewards were manipulated in order to determine if external rewards provide another replenishment mechanism that can attenuate the vigilance decrement. Since it has been shown that external rewards impact the vigilance decrement (Horne, et al., 1985; Bonnefond, et al., 2011), this would provide further support that external rewards are an additional replenishment mechanism in sustained attention. This would also provide further support for the reward component of the MTFR. It was hypothesized that an external reward functions similar to an internal reward, and that less cognitive slowing would occur with increased external rewards. It is predicted that less slowing will occur at each stage of processing when external rewards are greater – resulting in an attenuation of the vigilance decrement.

In Experiment 2 the medium event rate condition was removed from the experiment. The reason that this condition was removed was because many of the effects identified in Experiment 1 were due to differences between the fast event rate and slow event rate condition. Specifically, there were significant differences over time between the slow and fast event rate conditions for all the dependent variable related to both the performance data and the perceptual data. Moreover, the MTFR makes the strongest predictions at the extremes of the event rate manipulation.

Another aim of Experiment 2 was to replicate the effects found in Experiment 1. This included the event rate effect, the cognitive slowing effect, and the correlation between the vigilance decrement and sleepiness, as evaluated by the ESS. The event rate effect refers to the finding that the vigilance decrement is steeper in faster event rate conditions. The cognitive slowing effect refers to the finding that more slowing occurs in earlier stages of processing the stimuli and that this slowing is a major cause of sustained attention errors. It is also important to see if there is a significant correlation between the ESS and the vigilance decrement, as a marginal correlation was found in Experiment 1.

Developing a comprehensive model of sustained attention was also important for this research – making it important that the MTFR model developed from Experiment 1 generalized to Experiment 2. It was hypothesized that when generalizing the model developed in Experiment 1, the MTFR will produce similar fits to the data. These fits include the performance measure, including both hits (percentage correct on critical trials) and false alarms (percentage correct on neutral trials).

# CHAPTER SEVEN: STUDY 2 METHOD

**Participants**

115 George Mason University undergraduate students participated for course credit. All participation was voluntary and participants had normal or corrected-to-normal vision. Similar to experiment 1, when performing the task, participants' cell phones were temporarily taken away. One participant was eliminated because of a failure of the experiment software. One additional participant was eliminated because they were run in a different condition for the practice task and the main task. Another participant was eliminated from inclusion in the study based on poor practice performance. The average performance on critical trials for the final session of the practice was 79.7% accuracy on critical trials, with a standard deviation of 15.4%. In order to remain in the study participants were required to detect at least 50% of all critical trials that appeared in the final practice session. In total, 112 participants had their performance data analyzed. The sample of 112 participants included 72 females and 40 males. The average age of participants was 20.31 years old with a standard deviation of 2.98 years.

While performance data was analyzed for all 112 participants, eye data for one participant was eliminated because the experimenter forgot to activate the eye tracker. Six additional participants' eye data were eliminated because of an error with the eye tracker. Eye data for thirteen participants were eliminated because no fixations occurred on more than 50% of trials in a block, resulting in unreliable data. In total, 92 participants had their eye data analyzed.

Additionally, trials were eliminated from the eye data analysis if there were no fixations for that trial. Eliminating trials based on no eye fixations caused <5 % of the trials to be excluded from the eye data analysis.

**Materials**

The materials were identical to experiment 1.

**Design**

Participants were randomly assigned to one of four conditions in a between groups 2 X 2 design where event rate (fast event rate vs slow event rate) and motivation (motivation vs no motivation) were crossed. In the fast event rate conditions a trial was presented every 1600 ms and in the slow event rate conditions a trial was presented every 3200 ms. In the motivation conditions, participants were shown a webcam and told that they were being video recorded. Additionally, participants were entered into a raffle where they had the opportunity to win a $20 Amazon gift card based on their performance. Participants were given 40 tickets to be entered into a raffle and for every incorrect answer a ticket was taken away, reducing the likelihood that the participant would win the gift card.

**Procedure**

The procedure was identical to Experiment 1 with a few exceptions that regarded the motivation condition. In the motivation condition a webcam was stationed on top of the computer monitor. Participants were told that they were being recorded prior to beginning the main task. Participants were also told that the experimenter was observing their performance in the room next to them. Prior to beginning the main task, participants in the motivation condition were also told that they would get a $20 gift card to amazon.com based on their performance. The gift card was based on a raffle system, and participants were told that they initially had 40 tickets entered into a raffle, and that one ticket would be taken away for every wrong answer. Participants were told that the more correct answers that were made, the greater the likelihood that they would receive the gift card.

**Measures**

The measures were identical to experiment 1.

# CHAPTER EIGHT: STUDY 2 RESULTS AND DISCUSSION

## Data preparation

The analysis approach and data preparation was identical to study 1.

## A Mixed Effects Model of the Vigilance Decrement For the Study 2 Manipulations

A similar approach as Experiment 1 was used in order to determine the most appropriate mixed effects model for Experiment 2. In a series of models (see Appendix D), it was found that adding the motivation manipulation did not improve the model fit. Similar to Experiment 1, the mixed effects model that best fit the data was a model that included event rate and time-on-task as a fixed factor and subject as a random factor with the slope for time-on-task allowed to vary for each participant.

Performance declined over time ($z = -5.31$, $p < .05$). There was an effect of event rate ($z = 2.26$, $p < .05$) where there was worse performance for faster event rate conditions. There was a marginal interaction between time-on-task and event rate ($z = 1.83$, $p = .07$). There was no main effect of motivation ($z = .05$, $p = .96$), no interaction between motivation and time-on-task ($z = 1.08$, $p = .28$), no interaction between motivation and event rate ($z = -0.45$, $p = .65$), and no three-way interaction between motivation, event rate, and time-on-task ($z = -0.86$, $p = .39$). (see Figure 16 and Table 6).

These findings generally support the findings of Experiment 1, namely, the interaction between time-on-task and event rate. However, a marginal interaction was found instead of a significant interaction. The finding that external motivation did not attenuate the vigilance decrement was counter to the hypothesis. One possible reason that no effect was found was that the manipulations of being monitored and getting a monetary reward of $20 were not strong enough manipulations. Since motivation was not a significant variable, it was not included in the forthcoming analyses, which were used in order to determine whether the effects found in Experiment 1 replicated.

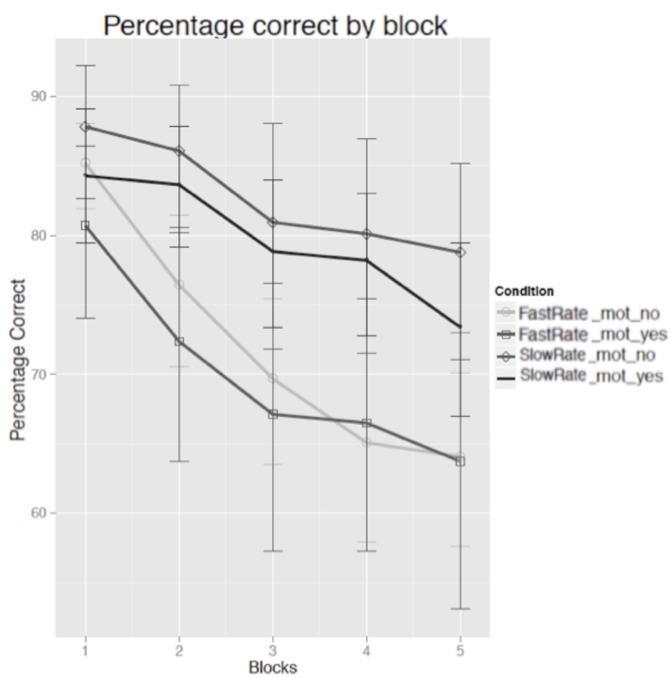



**Figure 16. Experiment 2 Critical Trial Accuracy. Percentage correct for critical trials is on the y-axis and block is on the x-axis. Each block was eight minutes long. Accuracy on the three event rate conditions is plotted. Error bars are 95% confidence intervals.**

**Table 6. Experiment 2 critical trial accuracy. Mean critical trial accuracy across blocks for the three event rate conditions. The items in parentheses are standard deviations.**

| | **Fast Event Rate / No Motivation** | **Fast Event Rate / Motivation** | **Slow Event Rate / No Motivation** | **Slow Event Rate / Motivation** |
|---|---|---|---|---|
| **Block 1** | 85.20% (8.15%) | 80.71% (16.10%) | 87.82% (13.25%) | 84.29% (13.19%) |
| **Block 2** | 76.44% (15.40%) | 72.38% (23.00%) | 86.09% (14.06%) | 83.65% (11.18%) |
| **Block 3** | 69.68% (16.77%) | 67.13% (26.44%) | 80.94% (23.32%) | 78.85% (14.76%) |
| **Block 4** | 65.09% (18.81%) | 66.51% (24.91%) | 80.12% (22.04%) | 78.21% (13.96%) |
| **Block 5** | 64.08% (17.62%) | 63.73% (27.54%) | 78.79% (19.86%) | 73.40% (16.50%) |

**Experiment 2 Mixed Effects Models of Neutral Trials**

For neutral trials, the mixed effects model replicated the event rate effect found in Experiment 1 where there were more false alarms in slower event rate conditions (see Table 7). There was an effect of event rate ($z$ = -6.49, $p$ < .05), a marginal effect of block ($z$ = 1.74, $p$ = .08), and no interaction between event rate and block ($z$ = -.69, $p$ = .49).

The neutral trial results supported the novel finding regarding false alarms, where more false alarms occur in slower event rate conditions. One explanation for the event rate effect is based on how ACT-R processes information. In slow event rate conditions there were longer trial durations, and as a result, there was more opportunity for a respond cognitive action to occur for slower event rate conditions.

**Table 7. Experiment 2 neutral trial accuracy. Mean neutral trial accuracy across block for the event rate conditions that are collapsed across the motivation manipulation. The items in parentheses are standard deviations.**

## Replication of the Cognitive Slowing Effect

The eye movement data were analyzed identically to how they were analyzed in Experiment 1. The eye movement data were analyzed in order to determine if the hypothesized pattern of slowing in perceptual data were replicated in Experiment 2. Recall that based on the predictions from MTFR, more slowing was hypothesized in faster event rate conditions and earlier in the processing of a stimulus. The MTFR makes these predictions due to replenishment mechanisms of opportunistic task breaks and internal rewards.

## Replication of Stage One of Processing

For the first stage of processing, participants took longer to look at the first stimulus as over time, ($t(87.50) = 3.98$, $p < .05$). There was a main effect of event rate, ($t(90.03) = 2.23$, $p < .05$), where participants were slower in the slow event rate condition. There was a marginal interaction between event rate and time-on-task, ($t(93.50) = -2.02$, $p < .05$) (see Figure 17).

In Experiment 1, there was a significant interaction between event rate and time-on-task, where participants were increasingly slower over time for faster event rate conditions. While the effect in Experiment 2 was marginal, it was in the same hypothesized pattern based on the predictions made from MTFR.

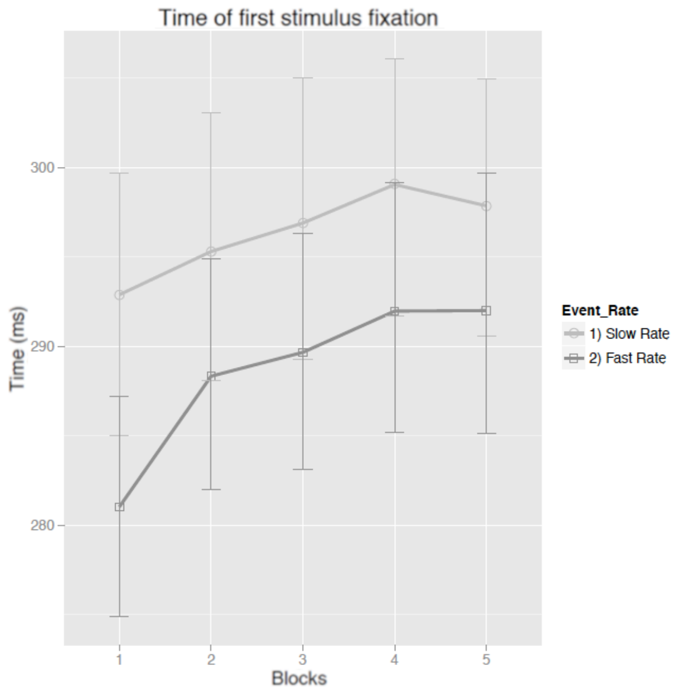



**Figure 17. Experiment 2 time to look at first stimulus. Time in milliseconds is on the y-axis, block is on the x-axis, and the different event rate conditions are compared for how long it took participants to look at the first stimulus.**

**Replication of Stage Two of Processing**

Next, the time between looking at the first stimulus and looking at the second stimulus was analyzed. There was a main effect of time, ($t(89.29) = 2.08$, $p < .05$). There was no effect of event rate, ($t(90.83) = 0.70$, $p = .49$). There was a replication of the interaction found in Experiment 1 between event rate and time-on-task, ($t(93.66) = -2.10$, $p < .05$) (see Figure 18), where for faster event rate condition more slowing occurred over time, but for the slow event rate condition, less slowing occurred over time.

This pattern of slowing supported the task break replenishment mechanism and the internal reward replenishment mechanism posited by the MTFR. The explanation for this effect posited by MTFR is that in slow event rate conditions, when more opportunistic task breaks occur, the impact of internal rewards and learning on performance can outweigh the impact of microlapses. As a result, there is more slowing over time in the fast event rate condition, but less slowing over time in the slow event rate condition.

The MTFR also predicts that more slowing will occur earlier in processing than later in processing due to the proximity of internal rewards that occur when performing a sustained attention trial. Similar to Experiment 1, in order to explore the differences between the stages of processing, the stage of processing factor was added to the mixed effects model as a fixed factor and the first stage of processing was compared to the second stage of processing.

Consistent with the Experiment 1 findings, there was more slowing over time, ($t(316) = 5.41$, $p < .05$) and more slowing in faster event rate conditions, ($t(142) = 5.73$, $p < .05$). Participants were slower in earlier stages of processing, ($t(184300) = -52.54$, $p < .05$). There was a marginal interaction between time-on-task and event rate, ($t(406) = -1.88$, $p = .06$), and there was no three-way interaction between time-on-task, event rate, and stage of processing, ($t(184300) = -0.08$, $p = .94$). However, there was an interaction between time-on-task and stage of processing, ($t(184300) = -3.42$, $p < .05$), where participants were slower to look at the stimulus over time in the first stage of processing than the second stage of processing. Additionally, there was an interaction between event rate and stage of processing where participants, ($t(184300) = -8.12$, $p < .05$), where participants were slower to look at the stimulus for faster event rate conditions in the first stage of processing than the second stage of processing.

None of the other theories of sustained attention postulate this interaction between the stage of processing and time-on-task on the speed that information is processed. The MTF posits a similar rate of slowing for each of the stages of processing. Resource Theory and Schema Theory do not make prediction at this level of detail regarding how long it takes to process stimuli within a given trial. Only the MTFR predicts this interaction because of the internal reward replenishment component of the theory.

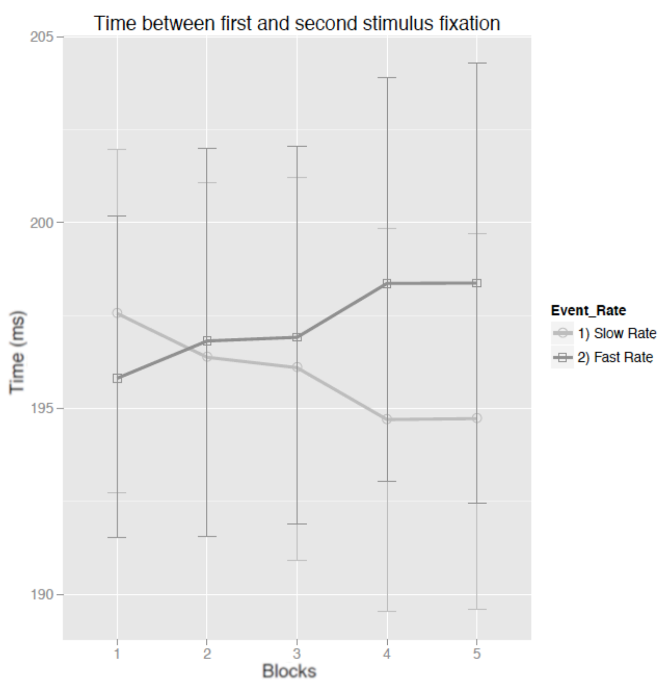



**Figure 18. Experiment 2 time between looking at the first and second stimulus. Time in milliseconds is on the y-axis, block is on the x-axis, and the different event rate conditions are compared for the time between how long it took participants to look at the first stimulus and the second stimulus.**

**Replication of Stage Three of Processing**

The third stage of processing involved the time between looking at the second stimulus and responding. There was a marginal effect of event rate, ($t(86.59) = 1.70$, $p = .09$), but there no main effect of time, ($t(77.93) = -0.14$, $p = .89$. Similar to Experiment 1, there was a marginal interaction between event rate and block where cognitive slowing over time occurred more for the slower event rate condition than the faster event rate condition, and the mixed effects model, ($t(82.72) = 1.87$, $p = .06$) (see Figure 19).

This again supported that there was an overall effect of cognitive slowing for this stage of processing. The replication of this finding from Experiment 1, supports the notion that one strategy that participants use in order to attenuate the vigilance decrement is to take their time to perform the task given that more time is provided to them. This suggests that participants may opportunistically decide to take task-contingent time-outs, even during the processing of a stimulus. According to MTFR, taking these strategic task-contingent time-outs may be an effective replenishment mechanism because it reduces the value of GDAT.

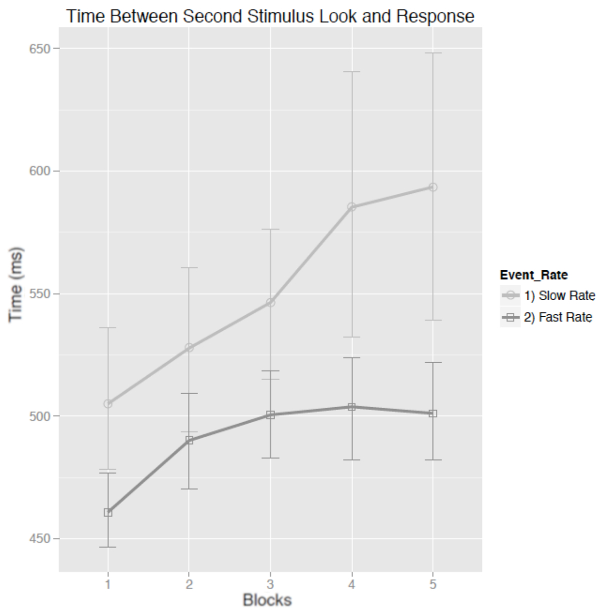



**Figure 19. Experiment 2 time between looking at the second stimulus and responding. Time in milliseconds is on the y-axis, block is on the x-axis, and the different event rate conditions are compared for the time between how long it took participants to look at the second stimulus and to respond.**

## Replication of the Not Looking As a Source of Errors Effect

Similar to Experiment 1, participants not looking at both stimuli increased with time on task, supporting the concept of PTEs. There was no effect of event rate on the percentage of time that both stimuli were looked at, ($t(90.34) = -0.15$, $p = .89$). There was an effect of time-on-task, ($t(89.62) = -4.42$, $p < .05$), where there was more slowing over time. There was a marginal interaction between event rate and time-on-task for the mixed effects model, ($t(91.89) = 1.80$, $p = .08$), where participants were increasingly less likely to look at both stimuli in the higher event rate conditions as time-on-task increased (see Figure 20).

These results were consistent with Experiment 1. The explanation for the interaction effect based on the MTFR is that more replenishment happens in the slow event rate conditions. Since according to MTFR, increased replenishment reduces GDAT and the likelihood of a microlapse, less slowing over time occurs in the slow event rate condition compared to the fast event rate condition. Since there is less slowing, there is a greater likelihood that the participant will be able to look at both stimuli in the slow event rate condition than the fast event rate condition. If there is not enough time to look at the stimulus, the participant will not be able to respond correctly to the trial.

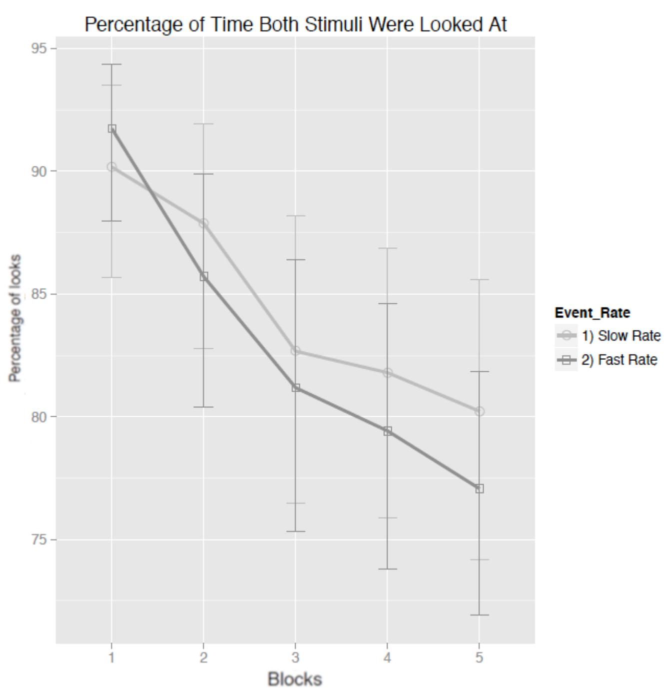



**Figure 20. Experiment 2 percentage of time that both stimuli were looked at. The percentage of time that both stimuli were fixated on is on the y-axis, block is on the x-axis, and the different event rate conditions are compared for the percentage of time that both stimuli were fixated on.**

**Replication of the Epworth Sleepiness Scale Effect**

Recall that in Experiment 1 there was a marginal negative correlation between the ESS and the slope of performance where more sleepiness was correlated with a steeper vigilance decrement where there was a significant negative correlation between the ESS and the slope of participant performance on critical trials, ($r(110) = -.19$, $p < .05$). In order to determine if this effect was driven by outliers, participants were eliminated if their Cook's distance value was above 4/n. This resulted in the elimination of six participants and a stronger negative correlation, ($r(104) = -.27$, $p < .05$) (see Appendix F). In other words, increased reported sleepiness on the ESS was correlated with a steeper vigilance decrement.

# CHAPTER NINE: STUDY 2 DISCUSSION

Counter to the hypothesis based on previous findings regarding the impact of external motivation on the vigilance decrement (Horne, et al., 1985; Bonnefond, et al., 2011), the external reward manipulations in Experiment 2 did not impact the severity of the vigilance decrement. One possible explanation for why external rewards did not impact the vigilance decrement is that the participant did not perceive the motivation manipulation as an important enough reward. Participants were told that they would be given the opportunity to win $20 based on the number of correct answers they gave and shown that they were being monitored. Horne et al.'s (1985) reward manipulation included providing a fixed amount for each correct answer and a penalty for each incorrect answer, as opposed to being entered into a raffle. Ensuring that the participants could win a certain amount of money instead of being in a raffle could possibly have this effect of attenuating the vigilance decrement using external rewards.

However, the results from Experiment 1 were replicated in Experiment 2, providing further support for the replenishment processes posited by the MTFR. The replicated results included, worse performance over time on critical trials as event rate increased, more slowing over time as event rate increased, and more slowing in the first stage of processing the stimuli than the second stage of processing the stimuli. Instead of the marginal correlation that was found in Experiment 1, in Experiment 2 there was a significant interaction between the ESS and the vigilance decrement where a more severe vigilance decrement was associated with more sleepiness ratings.

These empirical findings are consistent with MTFR. According to MTFR, more slowing occurs in faster event rate conditions because participants are less able to take opportunistic breaks, or what has previously been described as, task-contingent time-outs (Mark, et al., 1987). The result of being able to direct attention off of the task is that GDAT decreases and more replenishment occurs. This replenishment of the central executive control system results in a greater likelihood for cognitive actions to occur and reduces the likelihood of a microlapse.

As was predicted by the internal reward replenishment component of the MTFR, more cognitive slowing occurred in earlier stages of processing. This nuanced pattern in the eye movement data suggested that other processes, namely reinforcement learning, counteract the effects of the vigilance decrement. Cognitive processes that are closer to an internal reward are more likely to occur because they get more of the reward in temporal-discount learning. This supports the processes of temporal discount learning, as instantiated in ACT-R as utility learning (Sutton & Barto, 1998; Anderson 2007).

Instead of the marginal correlation between the ESS and the vigilance decrement that was found in Experiment 1, in Experiment 2, there was a significant relationship. Increased reported sleepiness on the ESS was correlated with a steeper vigilance decrement. This provided further support for both the MTF and the MTFR because these models include and explicit process of how fatigue related processes impact the vigilance decrement.

# CHAPTER TEN: GENERALIZING THE COMPREHENSIVE MODEL OF VIGILANCE

In order to determine the validity of the MTFR, the model developed from Experiment 1 was generalized to the Experiment 2 data using the identical parameters for the model from Experiment 1. A valid model will again fit the performance data, including the critical trial performance data and the neutral trial performance data. Recall that the model developed in Experiment 1 included setting fpmc to -.14, rpmc to 2.18, the reward to 3.5, and the response production utility to .4. Similar to Experiment 1, the model was run 100 times in each condition.

The model produced good fits to the data ($R^2$ = 0.93, *RMSE* = 4.63%) (see Figure 21). Importantly, the interaction between time-on-task and event rate was replicated, where performance declined at a faster rate as event rate increased. The model did not produce as good of fits as the model from Experiment 1 because other factors may impact the generalizability of the model, such as differences in participant's perceptual abilities and fatigue. The model could thus be further improved by using the same theoretical mechanisms but doing another parameter search in order to best fit the Experiment 2 data.

The generalizability of a comprehensive model of sustained attention can be further improved with a better understanding of individual participant variability. Differences in the vigilance decrement can be impacted by a number of factors that include:

psychomotor abilities, practice, initial fatigue levels, and motivation. Exploring the role of these factors could result in the improved generalization of computational models of the vigilance decrement.

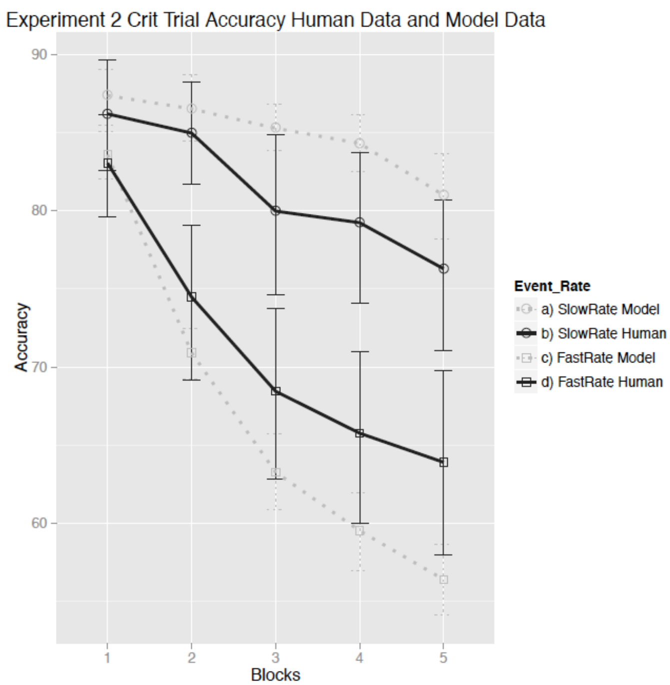



**Figure 21. MTFR generalization of the vigilance decrement. Human performance accuracy on critical trials compared to the ACT-R model using a version of ACT-R that includes the fatigue component of the MTFR and the reward component of the MTFR.**

In further support of the MTFR, the generalized MTFR model provided close fits to the false alarm effect (see Figure 22) ($R^2$ = 0.95, *RMSE* = 1.09%). There was no effect of time-on-task on the rate of false alarms, though there were more false alarms overall in the slow event rate condition. The reason the model produces this effect is that in slower event rate conditions, the trials are longer, which results in a greater likelihood of a response cognitive action to fire. Interestingly, the generalized model performed better than the model in Experiment 1 for the false alarm data. The correlation between the model and the experimental data is much higher in this experiment than Experiment 1 because in Experiment 1 this effect was not as strong as in Experiment 2. This provided further supporting for the main effect of event rate on false alarms.

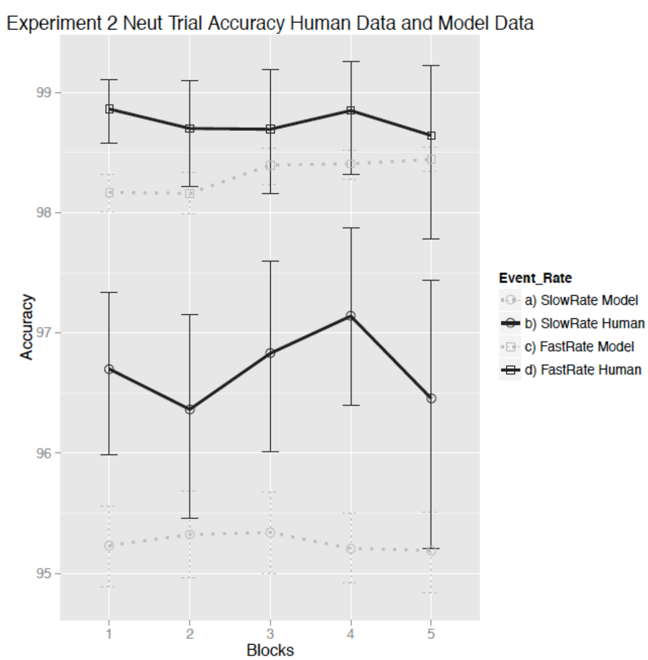



**Figure 22. MTFR generalization of the neutral trial effect. Human performance accuracy on neutral trials compared to the ACT-R model using a version of ACT-R that includes the fatigue component of the MTFR and the reward component of the MTFR.**

The generalized MTFR also replicated the cognitive slowing effect, where more slowing over time occurred in the first stage of processing than the second stage of processing. Similar to the experiment data, for the cognitive action of looking at the first stimulus, slowing occurred in both event rate conditions. However, for the second stage of processing, slowing only occurred in the fast event rate condition. The reason that the MTFR produces this effect is that cognitive actions that occur later in processing are temporally closer in proximity to the reward that is allocated when both stimuli are looked at. The effect where in the second stage of process the model gets faster over time again shows how utility learning and increased task break replenishment mechanisms can override the impact of microlapses in certain conditions.

While the MTFR developed in Experiment 1 did a good job generalizing to the Experiment 2 data, there are other ways to improve the MTFR in order to develop a comprehensive model of sustained attention. One way that was previously mentioned is with a better understanding of participants' psychomotor ability and level of fatigue. Another way is with a better understanding of the productions that are chosen to perform the task. The productions chosen for modeling the task may be slightly different than the cognitive actions that participants use to perform the sustained attention task, meaning again, that the psychomotor ability of participants needs to be better understood. Another way to improve the model is with a better understanding of the strategy that people use in order to know when to take a task break. The model did not make the prediction regarding the third stage of processing where as time-on-task increased participants took more time to respond in the slower event rate conditions. The reason for this is that the model only took breaks when no stimuli were perceived or being processed. Yet the human data suggest that breaks can also occur during the processing of a trial, when the participant can anticipate that they can take their time to respond.

# CHAPTER ELEVEN: GENERAL DISCUSSION

In this dissertation replenishment mechanisms posited by the MTFR were supported based on performance data, perceptual data, and survey data. The MTFR modified the MTF by replacing the time-on-task variable with the concept of GDAT, which differentiates between time spent attending to the task and time spent taking a break from the task. According to GDAT, when attention is directed away from the task at strategic times, such as when it not required based on task parameters, a task break occurs. When a task break occurs, this replenishes the cognitive resource related to central cognition, namely the resource responsible for the matching, selecting, and executing of cognitive actions. Replenishing this resource increases the likelihood that a cognitive action will occur, reduces the likelihood of a microlapse, and attenuates the vigilance decrement. The MTFR also modified the MTF based on a replenishment mechanism that relates to reinforcement learning in ACT-R (Anderson, 2007; Sutton & Barto, 1998), where small internal rewards that occur when successfully performing a task can also replenish this same resource and reduce the likelihood that a microlapse of attention will occur.

These replenishment mechanisms were supported in two experiments that manipulated the rate that stimuli appeared (the event rate) and measured the process of performing a sustained attention task by inducing eye movements in a novel paradigm. In support of the task break replenishment mechanism and the internal reward replenishment mechanism proposed by the MTFR, in Experiment 1 and Experiment 2 it was found that: (i) The vigilance decrement was steeper in faster event rate conditions, (ii) More slowing occurred over time in faster event rate conditions, and (iii) More slowing occurred earlier in the processing of a trial than later in the processing of a trial. While it was hypothesized by MTFR that external rewards are another replenishment mechanism that can attenuate the vigilance decrement, external rewards did not impact the vigilance decrement in the Experiment 2 manipulation.

These findings supported the MTFR over other theories of sustained attention. The MTF does not predict the interaction between event rate and time-on-task, while Resource Theory and Schema Theory do not describe the process whereby the vigilance decrement occurs at a level of detail necessary to make predictions regarding the pattern of slowing in the perceptual data and the relationship between the ESS and the vigilance decrement. Additionally, the MTFR could explain a nuanced finding in the perceptual data regarding the finding that cognitive actions increased in speed over time later in the processing of a trial in the slow event rate condition. This effect was found in both Experiment 1 and Experiment 2. According to the MTFR, cognitive actions can get faster over time when replenishment mechanisms outweigh the impact of microlapses. This may provide an explanation for why various tasks, such as playing video games, typically are not characterized by a vigilance decrement. In these cases, reward mechanisms may outweigh the impact of fatigue related processes.

In support of the MTFR and the event rate effect that was previously reported in the literature and predicted based on Resource Theory (Loeb & Binford, 1968; Lanzetta, Dember, Warm, & Berch, 1987; Davies & Parasuraman, 1982), in Experiment 1 it was found that there was a steeper vigilance decrement in faster event rate conditions and in Experiment 2 it was found that this was a marginal interaction. Moreover, by including the GDAT mechanism introduced by MTFR, the MTFR produced good fits to the data from Experiment 1 ($R^2$ = 0.95, *RMSE* = 2.15%) and the generalized model produced good fits to the data from Experiment 2 ($R^2$ = 0.93, *RMSE* = 4.63%). The MTF could not explain this effect and it is unclear what the prediction Schema Theory would make regarding the event rate and time-on-task interaction effect.

An unexpected effect was also found in Experiment 1 and Experiment 2 regarding neutral trial performance. It was found that in slower event rate conditions, participants were more likely to respond to neutral trial, *i.e.,* false alarm errors increased in slower event rate conditions. The MTFR replicated this effect because of how central cognition works in ACT-R. In ACT-R, a cognitive action fires when probabilistically, it exceeds a given threshold. Since slower event rate conditions have longer trial durations, this means that there is a greater likelihood that a cognitive action to respond will randomly exceed the given threshold, causing a false alarm. This is a novel mechanism proposed by the model to explain false alarm effects.

The perceptual data supported the theoretical mechanism of microlapses that underlies the process account of both the MTF and the MTFR. The MTF and the MTFR posit that the vigilance decrement is induced by brief gaps of attention that cause processing time errors, or PTEs. PTEs occur when the participant does not have enough time to look at, encode, and respond to a sustained attention trial. Increased cognitive slowing over time was detected at each stage of processing the sustained attention trial and not being able to look at both stimuli was identified as a major source of errors, supporting the process described by PTEs. Moreover, in faster event rate conditions, more slowing occurred over time than in slower event rate conditions and earlier in the processing of a trial. The MTFR was able to replicate these cognitive slowing effects that were identified in the perceptual data.

Counter to what was predicted based on the literature regarding the impact of external motivation on the vigilance decrement (Horne et al., 1985; Bonnefond, et al., 2011), in Experiment 2, external motivation did not attenuate the vigilance decrement. One explanation for this finding is that the participant did not consider the external motivation manipulations as a large enough incentive. This can be addressed in future research by providing participants with increased external rewards. Since Horne et al. (1985) only found an external motivation effect under conditions of sleep deprivation, the null effect found in this experiment when sleep deprivation was not induced suggests that it may be particularly difficult to effectively manipulate external motivation when participants are not sleep deprived.

In support of MTF and MTFR, which suggests that fatigue related processes impact the vigilance decrement (Gunzelmann et al., 2009; Gunzelmann et al., 2010; Veksler & Gunzelmann, *under revision*), in Experiment 1 and Experiment 2 there was a relationship between the vigilance decrement and reported sleepiness. In Experiment 1, a marginal correlation was found between the ESS and the vigilance decrement when increased sleepiness scores were related to a steeper vigilance decrement. This correlation was then found to be significant in Experiment 2. The MTF and the MTFR include fatigue mechanisms based on a biomathematical model of fatigue and that are related to the same mechanisms that produce the vigilance decrement. This correlation provides further support for the relationship between sleep related processes and the vigilance decrement that is proposed by these theories.

**Theoretical Contribution**

The goal of this research was to develop a comprehensive model of sustained attention that could precisely quantify the vigilance decrement by integrating a theory of sustained attention and fatigue with the ACT-R cognitive architecture. In order to accomplish this goal, it was necessary to develop a model that could account for the major effects that have been documented in the sustained attention literature (Davies & Parasuraman, 1982). When Davies & Parasuraman (1982) developed the vigilance taxonomy they identified many of these effects, including, the event rate effect, the memory effect, the modality effect, and the source complexity effect. Other effects that have been documented in the sustained attention literature include studies that found a steeper vigilance decrement with shorter signal duration (Baker, 1963), increased event rate (Loeb & Binford, 1968; Lanzetta, et al., 1987), increased uncertainty of stimuli (Scerbo et al., 1987), and increased use of memory (for meta-analysis reviews see Davies & Parasuraman, 1982 and See, Howe, Warm, Dember, 1995).

The MTFR can provide a theoretical explanation for all of these behavioral findings, thereby satisfying the goal of developing a comprehensive model of sustained attention. Veksler & Gunzelmann (*under revision*) first demonstrated that the MTF could explain sustained attention performance regarding the vigilance decrement in a conventional sustained attention task called the Mackworth Clock Task. The signal duration effect found by Baker (1963) was then modeled by the MTF where the model was able to fit the signal duration effect because microlapses differentially impacted conditions where there was less time for the operator to be able to process the stimuli in order to make a judgment (Gartenberg et al., 2014). Called processing time errors (PTEs), the same process level description was then used to explain the memory effect reported in the literature (Gartenberg et al., 2015; Gartenberg et al., *in prep*). As described by Gartenberg et al. (*in prep*), sustained attention tasks with increased memory show a steeper vigilance decrement because the additional step of making a memory retrieval results in the stimuli taking a longer amount of time for the operator to process. As a result sustained attention tasks with increased memory are relatively more impacted by microlapses. It was then theorized that a similar process could explain modality effects and source complexity effect, since different modalities take differing amount of times to process stimuli and increased stimuli complexity also results in longer processing time (Gartenberg et al., *in prep*).

In this research it was demonstrated that the theoretical mechanisms included in the MTF could not explain the event rate effect. It is important to be able to explain the event rate effect because processing stimuli quickly is related to attention, the main process thought to be depleted in sustained attention tasks (Davies & Parasuraman, 1982). This effect is theoretically important because Resource Theory predicts that as event rate increases, participants will show a steeper vigilance decrement, while Schema

Theory does not make a clear prediction regarding this effect. The event rate effect also is practically important because understanding the event rate effect can be useful in informing when to schedule operators for a task break.

By modifying the MTF to include a rest mechanism, the MTFR was able to fit this important effect. The MTF was modified by decrementing production utilities (and thus increasing microlapses) based on GDAT instead of time-on-task. GDAT takes into account instances of when attention is being allocated towards the task, and when attention is not required on the task. The GDAT process can also be used to explain the stimuli uncertainty effect (Scerbo et al., 1987). With a better understanding of when participants take opportunistic breaks from the task, a model can be developed that can simulate the stimuli uncertainty effect because when stimuli are presented at unpredictable times, it becomes more difficult for the participant to take a strategic break from the task.

Furthermore, the theoretical concept of GDAT provides an explanation as to why a simple reaction time task, such as the PVT, is the gold standard used to measure vigilance in the sleep literature (Dinges, Orne, Whitehouse, Orne, 1987; Van Dongen, Dinges, 2005), and similar types of tasks administered on a mobile device have also been shown to be sensitive to the components of sleep (Parasuraman & Gartenberg, 2010). The sensitivity of these tasks to detecting fatigue related processes might be because a feature of these tasks is that stimuli appear at irregular times. Irregular stimuli presentations prevents the participant from being able to take task contingent time-outs, resulting in more use of goal-directed attention and a task like the PVT that is highly sensitive to the vigilance decrement.

The GDAT mechanism of MTFR supports prior applied research, which suggests that providing operators with brief task breaks is an effective way to address the negative impact of the vigilance decrement (Stave, 1977; Ariga & Lleras, 2011). And because MTFR is a computational model that makes quantitative predictions regarding the rate of decline and recovery over the course of a sustained attention task, it provides a way to quantify the amount of break time that is required for an operator to alleviate the vigilance decrement. With this information, errors can be addressed in applied settings by being able to predict when an operator needs to take a break.

Taken together, the MTFR can explain the major findings included in the vigilance taxonomy (Davies & Parasuraman, 1982) and other research on sustained attention (Baker, 1963; Scerbo et al., 1987). However, MTFR has not yet been used to explain the effect of external motivation on sustained attention (Horne & Pettitt, 1985; Bonnefond, et al., 2011). Since no effect of external motivation was found in this study, MTFR was not used to generate this effect, though the internal reward mechanism included in the MTFR may be able to explain this effect in future research.

The mechanisms proposed by the MTFR are consistent with Resource Theory, but improve upon the theory by describing the process that underlies the vigilance decrement and specifying the resource that is depleted as the basal ganglia, a brain region that impacts the central executive attentional network's ability to match, select, and execute cognitive actions. Importantly, the MTFR provides a single theoretical account that can explain the various effects in the sustained attention literature, can make precise quantitative predictions, and can be generalized to various types of sustained attention task.

While the MTFR can explain the major effects in the literature, this does not eliminate the possibility that other resources can also be drained while performing sustained attention tasks. Typical sustained attention tasks may deplete central executive attentional processes, but other types of tasks that have different cognitive requirements, such as increased use of declarative memory load, may have an impact on a resource related to the activation of declarative facts (Halverson, et al., 2010). This possibility is consistent with use-dependence theory, which posits that the vigilance decrement is due to the repeated use of task specific neuron groups (Van Dongen, et al., 2010; Van Donger, et al., 2011). In certain circumstances other neuronal groups may be impacted by continuous use; however, this research suggests that in conventional sustained attention tasks, the neuronal group that is impacted is related to the basal ganglia and the ability to match, select, and execute cognitive actions.

**Methodological and Analytical Contribution**

The sustained attention task that was designed in this study to induce and measure eye movements improved upon the paradigm originally developed by Gartenberg et al. (*in prep*). These improvements included, (i) ensuring that participants were required to process two stimuli in order to make a judgment on whether or not to respond, (ii) using a mask in order to prevent post stimuli presentation processing, and (iii) adjusting the stimuli presentation time in order to induce a steeper vigilance decrement. These methodological improvements allowed for improved sensitivity in detecting the cognitive processes involved when performing a sustained attention task. This methodology can be used in future research in order to improve how well the vigilance decrement is understood, such as by including additional measures to the eye tracker, such as EEG, TCD, and fMRI.

An analysis issue was also identified that has implications for how most sustained attention tasks are analyzed. Typically, sustained attention tasks are analyzed using a regression ANOVA model, by collapsing the time-on-task variable into blocks. For example, if a sustained attention task has 1200 trials, time-on-task is segmented into four blocks, with the first 300 trials being included in the first block, and so on. These blocks are then entered into an ANOVA model. Granularity in the time-on-task variable is lost when block is used as a proxy for time-on-task in an ANOVA model, and this binning results in losing valuable information about the data.

**Conclusion**

A comprehensive model of sustained attention called the MTFR was developed that explained the major behavioral effects in the literature by modifying the MTF to including replenishment mechanisms. These replenishment mechanisms were used to model the event rate effect for the vigilance decrement and the pattern of slowing found in the perceptual data. The event rate effect was modeled by including a task continent time-outs mechanism based on GDAT. The finding that earlier cognitive actions had more slowing was modeled by using reinforcement learning in ACT-R. With these mechanisms added to the model, the perceptual behavior of participants related to the pattern of microlapses throughout the processing of a sustained attention trial was modeled. This research was another step in the effort to develop a comprehensive model of sustained attention that can explain the major effects in the literature, make quantitative predictions regarding the vigilance decrement, and generalize to various types of tasks. Ideally, a single model could be developed to inform the scheduling of workers, when workers need to take a break, and the types of tasks that workers can perform. This could reduce catastrophic error in and improve productivity in the workplace.

# APPENDIX A: EXPERIMENT 1 MIXED EFFECTS MODELS

The Experiment 1 analysis began with a simple mixed effects model that included time-on-task as a fixed factor and subject as a random factor, and it was assumed that each participant had a different y-intercept (see the below R code for the Time-on-Task-Model). The effect of time-on-task was significant ($z = -12.45$, $p < .05$), which supported that the vigilance decrement was induced by the sustained attention task.

*Time-on-Task-Model=glmer(accuracy ~ time-on-task + (1|Subject), family="binomial")*

Next, the fixed effect of event rate was introduced (see the below R code for the Event-Rate-Time-on-Task-Model) and compared with the Time-on-Task-Model. The effect of time-on-task was significant ($z = -9.115$, $p < .05$), lending further support that the sustained attention task induced a vigilance decrement. There was no effect of event rate ($z = 1.50$, $p = .13$). There was however an interaction between time-on-task and event rate ($z = 5.729$, $p < .05$). The interaction between event rate and time-on-task was consistent with the previous finding regarding the event rate and block interaction. Lastly, a Chi-squared was used to compare the event-rate-time-on-task-model to the time-on-task-model. The event-rate-time-on-task-model provided a better fit to the data when compared to the simple time-on-task-model ($\chi 2(2)=51.42$, $p < 0.05$).

*Event-Rate-Time-on-Task-Model = glmer(accuracy ~ event.rate * time-on-task + (1|Subject), family="binomial")*

In the next step, time-on-task was nested within subject in order to indicate that each participant experienced different rates of decline as time-on-task increased (see the below R code for the Event-Rate-Nested-Time-on-Task-Model). This model was then compared with the previous event-rate-time-on-task-model that did not assume that each participant had a different rate of decline as time-on-task increased. The effect of time-on-task was again significant ($z$ = -6.126, $p < .05$). Similar to the previous model, there was no effect of event rate ($z$ = 1.57, $p$ = .12); but there was an interaction between time-on-task and event rate ($z$ = 4.294, $p < .05$). The interaction between event rate and time-on-task supported the findings of both the previous model and the regression model, when as event rate increases, performance declines at a faster rate over time. When a Chi-squared was used to compare this nested subject model with the non-nested subject model that did not make an assumption regarding different rates of decline for each participant as time-on-task increased, the model that nested time-on-task within subject provided a better fit to the data ($\chi2(2)=34.51$, $p < 0.05$) (see Table 8 for a synopsis on the models). These findings suggested that a mixed effects model that nests time-on-task within subject and includes event rate as a fixed factor provides a best fit to the data, as is indicative of this model having the lowest AIC value (see Table 8).

*Event-Rate-Nested-Time-on-Task-Model = glmer(accuracy ~ event.rate * time-on-task + (time-on-task|Subject), family="binomial")*

**Table 8. Experiment 1 mixed effects model of hits comparisons. Note that in frequentist models the Akaike Information Criterion (AIC) measures the degree of model fit while correcting for the number of parameters – thereby providing a measure for model comparisons (Akiake, 1973). AIC provides an estimate of the quality of the models, where a lower AIC value represents a better model fit.**

| | **Df** | **AIC** | **Event Rate** | **Time-on-Task** | **Event Rate * Time-on-Task** |
|---|---|---|---|---|---|
| **Time-on-task-model** | 3 | 7096.0 | NA | $p < .05$ | NA |
| **Event-rate-time-on-task-model** | 5 | 7048.6 | $p = .13$ | $p < .05$ | $p < .05$ |
| **Event-rate-nested-time-on-task-model** | 7 | 7018.1 | $p = .12$ | $p < .05$ | $p < .05$ |

## APPENDIX B: MORE ERRORS WHEN DID NOT LOOK

```
print.output <- lrm(error ~ second.stim.looked, data=df.critical)
>       print(print.output)

Logistic Regression Model

lrm(formula = error ~ second.stim.looked, data = df.critical)

                        Model Likelihood     Discrimination    Rank Discrim.
                           Ratio Test           Indexes          Indexes
Obs          7179    LR chi2    1307.21     R2       0.244    C       0.733
 0           5319    d.f.             1     g        1.122    Dxy     0.466
 1           1860    Pr(> chi2) <0.0001     gr       3.071    gamma   0.808
max |deriv| 2e-09                           gp       0.179    tau-a   0.179
                                            Brier    0.160

                           Coef    S.E.   Wald Z Pr(>|Z|)
Intercept                  -0.2692 0.0332  -8.11 <0.0001
second.stim.looked -2.2453 0.0724 -31.00 <0.0001


>   GetROCValues(print.output, df.critical)
AUC = 0.7330912     TPR = 0.8596774     FPR = 0.393495     d' = 1.349092
```

Using a logistic regression, it was found that there was a greater likelihood of an error when the participant did not look at both stimuli.

# APPENDIX C: STEPS IN MODELING SUSTAINED ATTENTION TASKS

**Modeling the Sustained Attention Task Using Standard ACT-R**

Using a version of ACT-R that did not include fatigue mechanisms, the model performs at near ceiling for all of the event rate conditions (see Figure 23). The model performed close to ceiling due to the variability involved in how ACT-R processes information. In all the event rate conditions, the productions necessary to perform the task had time to fire within the 500 ms stimulus presentation window, resulting in no vigilance decrement and no differentiation between the event rate conditions. This modeling effort demonstrated that when no fatigue mechanisms are included in the model, the model does not produce the vigilance decrement effect and poorly fits the data ($R^2$ = .41, *RMSE* = 25.64%).

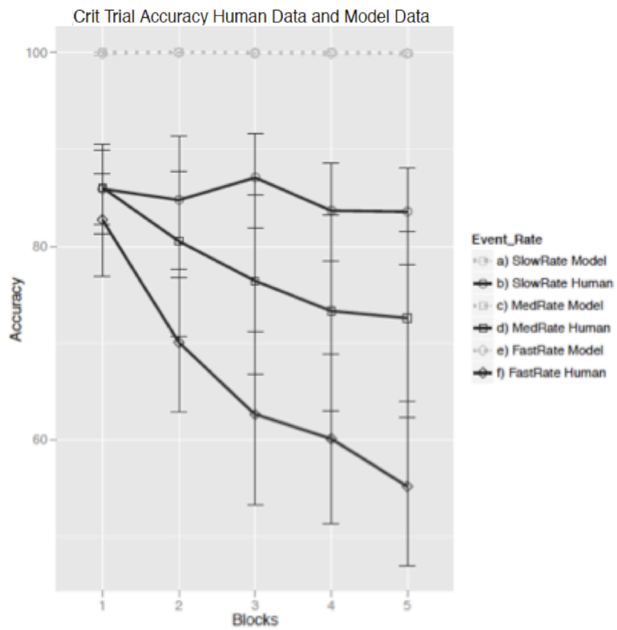



**Figure 23. Standard ACT-R model of the vigilance decrement. Human performance accuracy on critical trials compared to the ACT-R model using a standard version of ACT-R.**

Recall that that for neutral trials there was no time-on-task effect, suggesting that the mechanisms that impact the vigilance decrement did not impact false alarms. Since there was no effect of time-on-task on false alarms, this aspect of the data could be modeled using a version of ACT-R that did not include any fatigue related mechanisms. This was accomplished by adding an additional production that involved responding when no stimuli were presented on the screen. Such a production represents higher-level processes involved in these tasks, in which participants periodically respond when they do not encode a critical trial because they have anticipated that critical trials appear a certain percentage of the time.

Also recall that there were more false alarms in slower event rate conditions. The model also produced this effect because there is more time for the *false alarm response* production to fire in slower event rate conditions, since the trials are longer in slower event rate conditions. The $R^2$ value of .05% is poor, but the RMSE was only 1.32% and produced the effect where there were more false alarms overall as event rate got slower (see Figure 24).

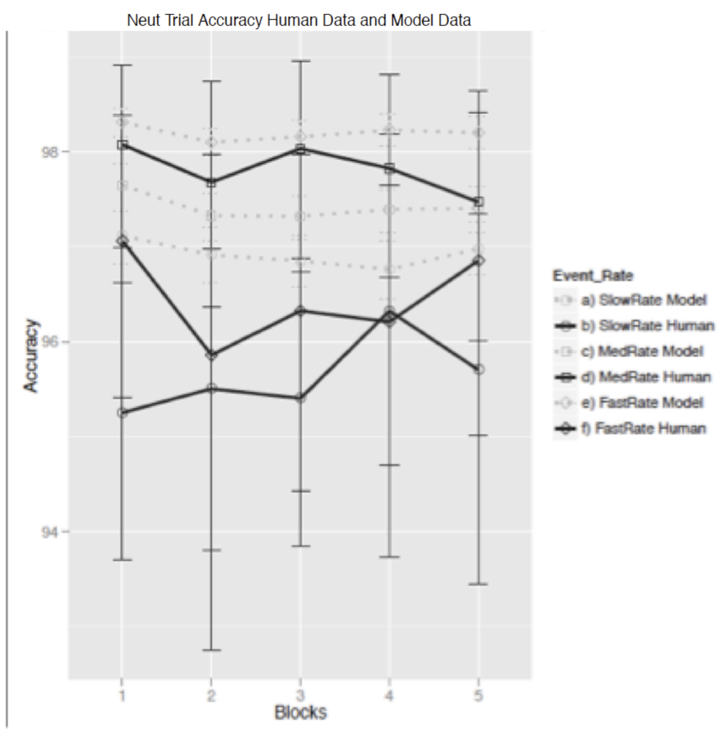



**Figure 24. Standard ACT-R model of neutral trials. Human performance accuracy on neutral trials compared to the ACT-R model using a standard version of ACT-R.**

**Modeling the Sustained Attention Task Using the MTF**

Since the version of ACT-R that does not include fatigue mechanisms does not produce a vigilance decrement, this indicates that fatigue related processes, such as those introduced by the MTF ought to be included in the ACT-R cognitive architecture (see Moore, Gunzelmann, Halverson, Veksler, Gluck, Krusmark, 2015). The MTF assumes that time-on-task impacts central cognition by reducing the utility of productions, resulting in small gaps in attention called microlapses, where no productions occur in a given production cycle. As a result, the model is less likely to respond to critical stimuli over time. Thus, when the participant is experiences time-on-task effects, the MTF posits that gaps in attention occur, resulting in more misses throughout the course of a sustained attention task.

To determine the appropriate value for fpmc, volunteer and high performance computing resources available through http://www.mindmodeling.org were leveraged (see Harris, 2008). The simulation determined that the optimal value for fpmc was -.04, consistent with the recommendation from Moore et al. (2015) that the fpmc value be between -1.0 and 0. All other parameters were set to the recommended defaults described by Moore et al. (2015). The model was run 100 times in each condition.

Using this approach of applying MTF to the ACT-R model that was developed, the model produced the vigilance decrement effect, but there was no effect of event rate (see Figure 25). The MTF did not produce an interaction between event rate and time-on-task, and it poorly fits the critical trial performance data ($R^2$ = .29, *RMSE* = 8.62%), because the model does not include any rest mechanisms. However, "task contingent time-outs" have been described in the literature (Mark, et al., 1987), wherein participants take strategic breaks, or brief rest periods between trials when anticipating that no response is required of them. The MTF does not include a description of this process, where participants in the slower event rate conditions have more time to take these task contingent time-outs and therefore experience an attenuation of the vigilance decrement. As a result of impacting production utility based on time-on-task alone, the MTF does not differentiate between the event rate conditions because all of the conditions had the same time-on-task.

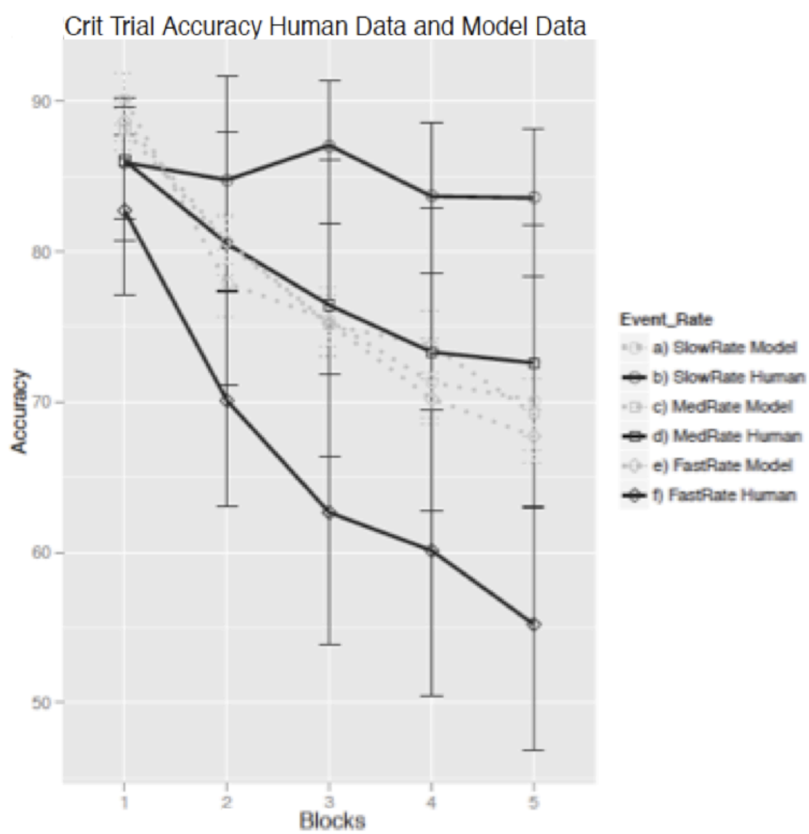



**Figure 25. MTF modification to the ACT-R model of the vigilance decrement. Human performance accuracy on critical trials compared to the ACT-R model using a modified version of ACT-R that includes the MTF.**

## APPENDIX D: EXPERIMENT 2 MIXED EFFECTS MODELS

Similar to Experiment 1, the modeling approach began with a simple model, which gradually became more complicated. First, the simple mixed effects model was run, which included time-on-task as a fixed factor and subject as a random factor (see the below R code for the Time-on-Task-Model). The mixed effects model was consistent with the regression model, and a significant time-on-task effect was found ($z = -14.25$, $p < .05$).

*Time-on-Task-Model=glmer(accuracy ~ time-on-task + (1|Subject), family="binomial")*

Next, the fixed effect of event rate was introduced and compared with the simple time-on-task-model (see the below R code for the Event-Rate-Time-on-Task-Model). Worse performance over time on critical trials was again found ($z = -6.51$, $p < .05$). Similar to the regression model, there was a main effect of event rate ($z = 2.07$, $p < .05$). There was a marginal interaction between event rate and time-on-task ($z = 1.90$, $p = .06$). The marginal interaction supports the previously reported finding that as event rate gets faster, performance declines more quickly over time. Moreover, when an Chi-squared was used to compare the event-rate-time-on-task model to the more simple time-on-task-model, the event-rate-time-on-task-model provided a better fit to the data ($\chi^2(2)=15.51$, p < 0.05).

*Event-Rate-Time-on-Task-Model = glmer(accuracy ~ time-on-task * event.rate + (1|Subject), family="binomial")*

The time-on-task variable was nested within subject based on the assumption that each participant experiences different rates of the vigilance decrement (see the below R code for the Event-Rate-Nested-Time-on-Task-Model). This model was then compared with the event-rate-time-on-task-model, where it was not assumed that there was a different rate of decline as time-on-task progressed. The effect of time-on-task was again significant ($z$ = -5.31, $p$ < .05). Similar to the event-rate-time-on-task-model, there was an effect of event rate ($z$ = 2.26, $p$ < .05). There was also again a marginal interaction between time-on-task and event rate ($z$ = 1.83, $p$ = .07). When a Chi-squared was used to compare this model with the event-rate-time-on-task-model, the event-rate-nested-time-on-task-model provided a significantly better fit to the data ($\chi2(2)$= 15.60, p < 0.05).

*Event-Rate-Nested-Time-on-Task-Model = glmer(accuracy ~ event.rate * time-on-task + (time-on-task|Subject), family="binomial")*

Lastly, motivation was added to the model (see the below R code for the Motivation-Event-Rate-Nested-Time-on-Task-Model). Again, a time-on-task effect was found ($z$ = -4.60, $p$ < .05) and there was a marginal interaction between time-on-task and event rate ($z$ = 1.87, $p$ = .06). Unlike the event-rate-nested-time-on-task-model, there was a marginal main effect of event rate instead of a significant main effect of event rate ($z$ = 1.95, $p$ = .05). There was no main effect of motivation ($z$ = .05, $p$ = .96), no interaction between motivation and time-on-task ($z$ = 1.08, $p$ = .28), no interaction between motivation and event rate ($z$ = -0.45, $p$ = .65), and no three-way interaction between motivation, event rate, and time-on-task ($z$ = -0.86, $p$ = .39).

The findings from the motivation-event-rate-nested-time-on-task-model indicated that the motivation manipulation was not a strong enough manipulation to impact the vigilance decrement. This suggested that a greater external reward is needed in order to induce an attenuation of the vigilance decrement. The AIC value was higher for the model that included motivation than the event-rate-nested-time-on-task-model. A higher AIC value indicates a worse model fit, which suggested that the event-rate-nested-time-on-task-model was the superior model. Moreover, when a Chi-squared was run between the motivation-event-rate-nested-time-on-task-model and the event-rate-nested-time-on-task-model, no significant difference between the models was found ($\chi 2(2)= 3.18$, $p = 0.53$). This provided support that the motivation manipulation was not an important variable to include in order explaining the data (see Table 9 for a synopsis on the models).

Motivation-Event-Rate-Nested-Time-on-Task-Model = *glmer(accuracy ~ event.rate * time-on-task * motivation + (time-on-task|Subject), family="binomial")*

**Table 9. Experiment 2 mixed effects model of hits comparisons.**

| | df | AIC | Event Rate | Time-on-Task | Motivation | Event Rate * Time-on-Task | Motivation * Time-on-Task | Motivation * Event Rate | Motivation * Time-on-Task * Event Rate |
|---|---|---|---|---|---|---|---|---|---|
| **Time-on-task-model** | 3 | 10086 | NA | $p < .05$ | NA | NA | NA | NA | NA |
| **Event-rate-time-on-task-model** | 5 | 10075 | $p < .05$ | $p < .05$ | NA | $p = .06$ | NA | NA | NA |
| **Event-rate-nested-time-on-task-model** | 7 | 10064 | $p < .05$ | $p < .05$ | NA | $p = .07$ | NA | NA | NA |
| **Motivation-event-rate-nested-time-on-task-model** | 11 | 10069 | $p = .05$ | $p < .05$ | $p = .96$ | $p = .06$ | $p = .28$ | $p = .65$ | $p = .39$ |

Motivation was not a significant variable and did not interact with any of the other variables in the experiment. Additionally, when adding motivation to the model, the AIC value increased. These findings indicate that the motivation manipulation did not impact the vigilance decrement. To determine if the motivation variable impacted participant performance, a mixed effects model was also run on neutral trials using the independent variables included in the motivation-event-rate-nested-time-on-task-model. Again, motivation was not found to impact the model (see Appendix D). Therefore, in all future analyses, the data were collapsed across motivation.

# APPENDIX E: A MIXED EFFECTS MODEL OF NEUTRAL TRIALS

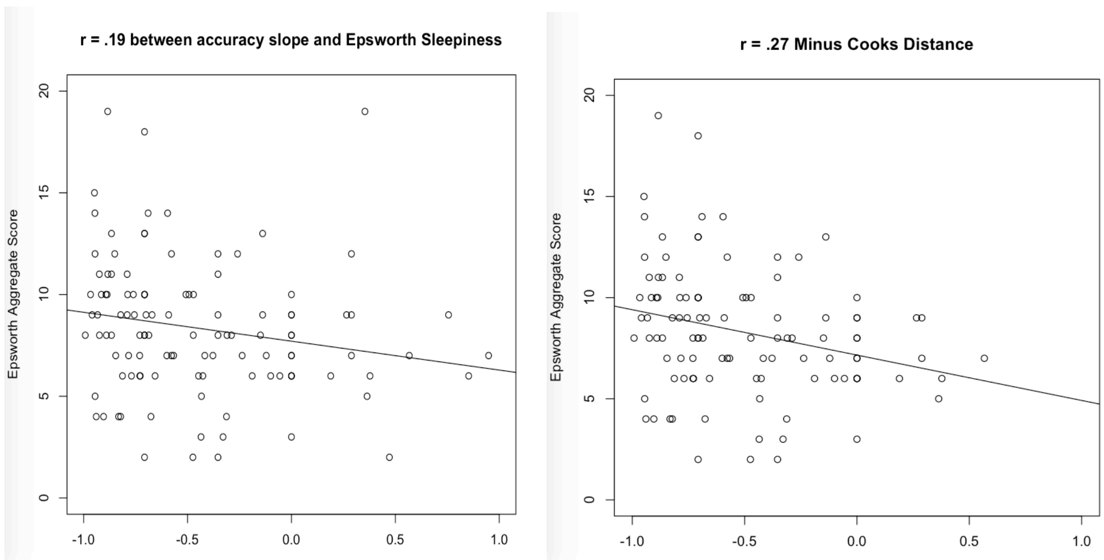
A mixed effects model was run to see how motivation, event rate, and time-on-task impacted neutral trial accuracy in experiment 2. Similar to experiment 1 there was only a main effect of event rate. There were no motivation effects found in the model.

Motivation-event-rate-nested-time-on-task-model = glmer(neutral_accuracy ~ event.rate * time-on-task * motivation + (time-on-task|subject), family="binomial")

**Table of mixed effects model of neutral trial accuracy that includes motivation as an independent variable.**

| | **df** | **AIC** | **Event Rate** | **Time-on-Task** | **Motivation** | **Event Rate * Time-on-Task** | **Motivation * Time-on-Task** | **Motivation * Event Rate** | **Motivation * Time-on-Task * Event Rate** |
|---|---|---|---|---|---|---|---|---|---|
| **Motivation-event-rate-nested-time-on-task-model** | 11 | 20076 | $p < .05$ | $p = .31$ | $p = .90$ | $p = .95$ | $p = .74$ | $p = .61$ | $p = .54$ |

# APPENDIX F: EPWORTH AND THE VIGILANCE DECREMENT CORRELATON




Experiment 2 correlation between Epworth Sleepiness Scale and the vigilance decrement where the left graph includes all participants and the right graphs includes participants that were eliminated based on Cook's distance.

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