

An ACT-R Process Model of the Signal Duration Phenomenon of Vigilance

Daniel Gartenberg¹, Bella Z. Veksler², Glenn Gunzelmann^{2,3}, J. Gregory Trafton³

George Mason University¹
Fairfax, VA

Air Force Research Laboratory²
Dayton, OH

Naval Research Laboratory³
Washington, DC

Performance on tasks that require sustained attention can be impacted by various factors that include: signal duration, the use of declarative memory in the task, the frequency of critical stimuli that require a response, and the event-rate of the stimuli. A viable model of the ability to maintain vigilance ought to account for these phenomena. In this paper, we focus on one of these critical factors: signal duration. For this we use results from Baker (1963), who manipulated signal duration in a clock task where the second hand moved in a continuous swipe motion. The critical stimuli were stoppages of the hand that lasted for 200, 300, 400, 600, or 800 ms. The results provided evidence for an interaction between condition and time-on-task, where performance declined at a faster rate as the signal duration decreased. In this paper, we describe an ACT-R model that uses fatigue mechanisms from Gunzelmann et al. (2009) that were proposed to account for the impact of sleep loss on sustained attention performance. The research demonstrates how those same mechanisms can be used to understand vigilance task performance. This illustrates an important foundation for predicting and tracking vigilance decrements in applied settings, and validates a mechanism that creates a theoretical link between the vigilance decrement and sleep loss.

INTRODUCTION

Humans are increasingly taking on the responsibility of supervisor of complex systems, resulting in situations where sustained attention and vigilance are becoming more taxed, while the potential consequences of errors are becoming more severe. These challenges extend across domains, including power plant workers, baggage handlers, air traffic controllers, military personnel, and pilots. The implications for safety have been documented in a variety of areas, with fatigue having been implicated in a number of disasters and naturalistic tasks (Mitler, Carskadon, Czeisler, Dement, Dinges, & Graeber, 1988; Horne & Reyner, 1999; Caldwell, 2003; Mallis, Banks, & Dinges, 2007; Shaw, Matthews, Warm, Finomore, Silverman, & Costa, 2010). Understanding the factors that impact vigilance performance can be used to prevent vigilance errors.

The factors that have been known to impact vigilance performance include: signal duration (Adams, 1956; Baker, 1963; Warm, Loeb, & Alluisi, 1970), the use of declarative memory in the task (Davies & Parasuraman, 1982; Warm & Dember, 1998), source complexity (Craig, Colquhoun, & Corcoran, 1976; Caggiano & Parasuraman, 2004), and the event-rate of the stimuli (Jerison & Pickett, 1964; Parasuraman & Davies, 1977). The resource theory of vigilance can account for many of these findings (Parasuraman & Davies, 1977; Wickens, 1984). According to resource theory, the decrement in performance that accompanies vigilance tasks is due to a decline in information processing resources. These resources are impacted by a number of factors, in particular, the fatigue and alertness system (Lim, Wi, Wang, et al., 2010). Because vigilance tasks require sustained attention and are stressful (Warm, Parasuraman, & Matthews, 2008), they impact resource availability, resulting in a decline in performance with time-on-task. As a result, tasks that are more difficult, with shorter signal durations, increased declarative memory load, and

increased event rate of stimuli cause greater decrements in performance.

While there is significant empirical evidence implicating factors that impact vigilance performance (Davies & Parasuraman, 1982), precise quantitative predictions are rare. The difficulty of quantifying vigilance performance is due, in part, to the variability in the processing requirements for different vigilance tasks. To explain findings across these various vigilance tasks, a cognitive architecture is a useful tool because of its ability to provide theoretical mechanisms to represent the various components of cognition.

Recently, Gunzelmann et al., (2009) proposed a set of mechanisms to account for the deleterious impacts of sleep loss on cognitive performance. The mechanisms were integrated into the Adaptive Control of Thought – Rational (ACT-R) cognitive architecture. The primary impact of the mechanisms is to introduce brief disruptions in goal-directed processing, called microlapses. Microlapses cause degradations in performance on sustained attention tasks, including increased response times, response lapses, and response failures. The microlapse mechanism provides a theory that can be used to link fatigue to vigilance. Importantly, the microlapse theory does this within a cognitive architecture – enabling quantitative predictions about human performance.

The ACT-R integration with microlapse theory closely fit declines in performance based on sleep deprivation (Gunzelmann et al., 2009), time of day effects (Gunzelmann et al., 2009), and time on task effects (Gunzelmann et al., 2010; Veksler & Gunzelmann, 2013). Of particular relevance to this research is recent efforts to extend this research to the vigilance decrement. Veksler and Gunzelmann (2013) demonstrated that micro-lapses provided an account of performance decrements in a frequently used vigilance task, known as the Mackworth Clock Task (Mackworth, 1948). However, important questions remain regarding the extent to which microlapses can provide a general and robust account of the vigilance decrement. Moreover, while the vigilance

decrement has been modeled using this method, many major phenomena that characterize the vigilance decrement have not yet been modeled, such as the signal duration effect, the role that memory plays in vigilance, and the event rate effect.

One of the most robust findings in the vigilance literature is the signal duration effect (Adams, 1956; Baker, 1963a; Warm, et al., 1970). Baker (1963) demonstrated the robustness of the signal duration effect by parametrically manipulating the signal duration in a Clock Test from 200ms to 800ms. Critical signals were stoppages of a continuously rotating second hand. In addition to a main effect of signal duration, where participants performed worse when the signal was shorter, the decrement in performance was steeper with shorter signal durations (see Figure 1).

There is currently no process model that explains the signal duration effect found in vigilance tasks. Here we demonstrate that microlapses, integrated into an ACT-R model that performs the task, is able to account for the main effects found in Baker (1963), as well as the interaction. Since the model produces precise quantitative fits, it also explains the fine-grained changes in human performance over the course of Baker's vigilance task. In the remainder of this paper, we present a model of the integration of ACT-R with micro-lapse theory and apply that framework to model the dataset reported by Baker (1963). We show the model's performance and the close correspondence to the human data.

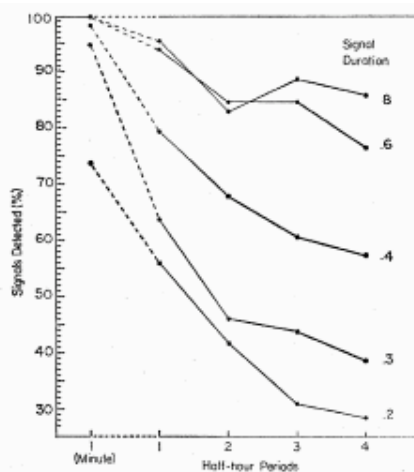


Figure 1. Data from Baker (1963), showing the percentage of signals detected during a 1-minute task (first point) and during each half-hour of a 2-hour task (remaining points), with differing signal durations.

METHOD

We based our model on the experiment data found in Baker (1963). Baker recruited 63 participants to perform the Clock Test on two occasions. The Clock Test involved a secondhand dial that made a continuous sweep around the clock face (completing one full cycle per minute). Critical signals were brief stoppages of the clock hand, which lasted for 200, 300, 400, 600, or 800ms.

On the first occasion, participants performed the Clock

Task for 50 minutes. One of the five signal durations was presented each minute, with each signal repeated 10 times over the course of the study. In the second session, performance was measured over a 2-hour period, each signal duration was presented once within each 15-minute block. As a result, signals occurred every 3 minutes on average, and a total of 40 signals were presented during the 2-hour session.

As demonstrated in Figure 1, performance varied widely across the different signal duration conditions – varying from 28% accuracy to 100% accuracy. Baker (1963) found a significant decrement, a signal duration effect, and an interaction between the time-on-task decrement in performance and signal duration.

MODEL

The main purpose of the model was to determine if Baker's (1963) findings regarding signal duration effects could be fit using the ACT-R cognitive architecture in conjunction with microlapse theory. The model that we developed draws on previous research on how sustained attention performance is impacted by sleep loss (Gunzelmann et al., 2009), time-on-task (Gunzelmann et al., 2010), and vigilance (Gunzelmann et al., 2013; Veksler & Gunzelmann, 2013).

ACT-R is a general theory of cognition that provides a framework for information processing because ACT-R posits a number of modules that incorporate quantitative theories representing different components of cognition (Anderson, 2007). These include: a central cognition system that coordinates actions, visual and auditory modules implementing perceptual capabilities, motor action, goal maintenance, declarative knowledge, imaginal processing, and other aspects of cognition. The amount of time that it takes for these modules to process information is influential in accounting for the signal duration effect found in the vigilance literature.

Of particular importance for the current model is the central cognition system. Baker's (1963) vigilance task requires visual attention, where the task is initiated with the following production rules:

- 1) (*find*) when the task begins, find the clock hand on the computer screen.
- 2) (*attend*) once the clock hand is found, visually attend to the hand.

When these first two production rules fire, the model attends to the clock hand as it moves around the clock face. For the rest of the task, the only two other production rules that fire are:

- 3) (*check*) if the visual module detects a screen change, do nothing.
- 4) (*respond*) if the visual module does not detect a screen change, press the spacebar.

A production's firing rate is integral to task performance in the current context. The amount of time that it takes for a production rule to fire in ACT-R is based on research

involving 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, Bekolay, & Eliasmith, 2012). The default version of ACT-R has the default setting of 50 ms as production cycle time. This would produce 100% accuracy in every condition of the Baker (1963) task because the shortest critical signal is 200 ms, a longer amount of time than the default cycle time. Therefore, using the default version of ACT-R would lead to either the *check* or *respond* production firing approximately every 50 ms, which is more than sufficient to produce perfect performance in the task.

Microlapses

Humans do not perform the task at 100% because humans are unable to perform well on sustained attention tasks for prolonged periods of time. Gunzelmann et al.’s (2009) microlapse theory addressed this by positing that fatigue impacts central cognition by reducing the utility of productions, resulting in no productions being fired and producing small gaps in attention and goal-directed processing. As a result, it takes a longer amount of time for a response to occur because productions fire less often. In the case of extreme fatigue, it can take as long as 30 seconds for a production to fire (Gunzelmann et al., 2009). Microlapse theory posits that these lapses occur in central cognition based on a large body of research showing the impact of fatigue on the basal ganglia – where a recent fMRI study on the neural basis of the vigilance decrement, showed that the vigilance decrement activated a right fronto-parietal attentional network that lateralized to the basal ganglia and sensorimotor cortices (Lim et al., 2010).

The result of microlapses is that productions will fire less reliably as time on task increases, causing a decreased likelihood of responding to a critical stimulus over time, with larger impacts when the signal duration is short. Gunzelmann et al. (2009) also proposed a compensation mechanism for these microlapses. To account for the role of effort, the utility threshold was lowered. This is the threshold that a production’s utility value needs to surpass in order to fire. This makes it more likely that some production will fire, but also increase the likelihood that an inappropriate action will be performed. The dynamics of this aspect of the account explains false alarms that often emerge during the performance of vigilance tasks. These two mechanisms account for the pattern of lapses and slowing of reaction time that is frequently found in sustained attention tasks (Doran, Van Dongen, Dinges, 2001).

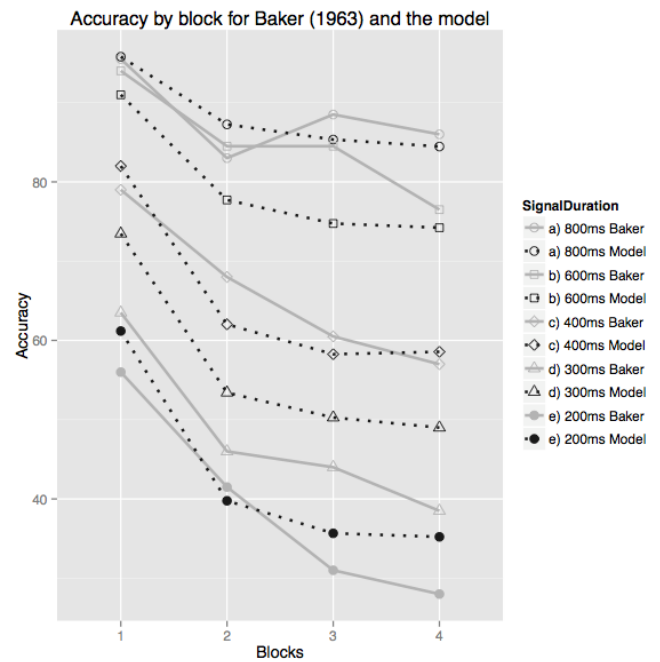
When the participant is fatigued, the microlapse theory posits that gaps in attention occur because no productions fire and the wrong productions are more likely to fire due to the compensation of the utility threshold. Progressive changes to parameter values with time on task cause microlapses to become more likely as time increases. This results in more misses as time on task increases, with a larger effect when the stimuli are presented for a shorter duration of time.

Changes in the parameter values of the micro-lapses were constrained using a power function. The use of the power

function was supported by previous research showing that a double exponential function characterized vigilance and that a power function could also fit these data (Giambra & Quilter, 1987). To identify the best-fitting power function for each parameter, volunteer and high performance computing resources were leveraged (see <http://mindmodeling.org/>; Harris, 2008). A similar procedure was used in Gunzelmann, et al. (2010) to determine the rate for which the production utility and production utility threshold decline over time to account for performance change with time on task in a sustained attention task. Based on the output from mindmodeling.org, the x-intercept of the production utility was set to 2.2 and the slope was set to -1. The x-intercept of the production utility threshold was set to 0 and the slope was set to .5.

Model Run

The ACT-R model was run 400 times using the same conditions and parameters as Baker (1963). Each model run performed the simulated task that the participant performed. Each time the model was run it was exposed to all of the signal duration conditions. Similar to Baker (1963), one signal from each signal duration occurred every 15 minutes.



RESULTS AND DISCUSSION

Figure 2. The graph shows participant accuracy and model accuracy the Baker (1963) task. Blocks are 30-minute increments of time. The solid lines represent Baker’s (1963) data and the dotted lines represent the model output. Note that we did not model the 1-minute task from Baker (1963).

Recall that Baker (1963) found a main effect of time-on-task, a main effect of signal duration, and an interaction between time-on-task and signal duration. (see Figure 1). The model replicates these effects and closely fits the data. The model accounted for 94.22% of the variance of the observed data for critical trials ($R^2 = .94$, $RMSE = 5.68\%$), percentile $R^2 > .99$ (Khemlani & Traflet, *under review*). These fits replicate Baker's (1963) findings and demonstrate that the ACT-R integration with microlapse theory can account for fine-grained quantitative results of the study. In addition to validating the qualitative findings of Baker (1963a), the model can quantitatively fit the fine-grained trends in vigilance performance.

According to the model, the decrement occurs because the probability of microlapses increases with time-on-task due to fatigue. As a result, participants are more likely to miss attending to the critical signal over time. For similar reasons, there is an effect of signal duration. Since microlapses result in small gaps in attention that can grow in duration as more occur in sequence, the model is more likely to miss shorter duration signals. The interaction between time-on-task and signal duration found in the model has to do with the differential impact that microlapses have on different signal duration conditions. When microlapses occur in a shorter signal duration condition, fewer are needed to produce an error, whereas many more microlapses are required to cause the model to miss a signal if the signal duration is longer. In other words, longer stimuli durations result in more processing tolerance, where a lapse of attention is less likely to impact performance.

CONCLUSION

In this paper we developed a model that fit data from Baker (1963), providing further validation for microlapses as a mechanism for fatigue and vigilance in ACT-R's integration with micro-lapse theory. In addition to modeling the decrement in performance and the condition effect of signal duration, where shorter durations are more difficult, we also replicated the interaction between signal duration and the vigilance decrement. The model produces this interaction due to the differential impact that micro-lapses have on performance when signal duration varies.

One of the main reasons that the model produces this interaction is due to the information processing constraints of the ACT-R cognitive architecture. For the Baker task, the model could detect a critical trial after as soon as 50 ms because ACT-R's production cycle time can be as short as 50 ms in duration. If ACT-R's production cycle time had been 200 ms, then the model would be unable to perform the task in the 200 ms condition – and model performance would be much worse. This suggests that if the processing of a stimulus takes a longer amount of time then the decrement will be more severe. This is in line with the finding that tasks with a declarative load are typically more difficult, but only when perceptual requirements are low (Warm & Dember, 1998). The model also suggests that the reason for this finding is that declarative retrievals typically take longer than perceptual discriminations.

This paper provides a framework for how ACT-R can be used to understand performance in a large number of vigilance tasks, by being able to account for the important variable of signal duration. However, to more completely validate the integration of microlapses into ACT-R, the model should account for the wide range of findings related to the vigilance decrement, including: the use of declarative memory in the task, the frequency of critical stimuli that require a response, and the event-rate of the stimuli. This is a ripe field for future research.

If vigilance can be modeled quantitatively in a cognitive architecture, there is broad potential to use models to evaluate how operators will perform at the workplace. This can inform the scheduling of operator work hours, the types of tasks that an operator ought to perform, and possibly the implementation of adaptive automation. Providing relief to the operator when it is needed and designing systems that do not overly tax an operator's vigilance can improve operator efficiency and reduce catastrophic errors in the work place.

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REFERENCES

- Adams, J. A. (1956). Vigilance in the detection of low-intensity visual stimuli. *Journal of Experimental Psychology*, 52, 205-208
- Amos, A. (2000). A computational model of information processing in the frontal cortex and basal ganglia. *Journal of Cognitive Neuroscience*, 12, 505-519.
- Anderson, J. R. (2007) *How Can the Human Mind Occur in the Physical Universe?* New York: Oxford University Press.
- Baker, C. H. (1963). Signal duration in a vigilance task. *Science*, 136, 46-47.
- Caldwell, J. A. (2003). Wake up to the importance of sleep for air safety! *Flightline*, 30-33.
- Caggiano, D.M., & Parasuraman, R. (2004). The role of memory representation in the vigilance decrement. *Psychonomic Bulletin & Review*, 11, 932-937.
- Craig, A., Colquhoun, W. P., & Corcoran, D. W. J. (1976). Combining evidence presented simultaneously to the eye and the ear: A comparison of some predictive models. *Perception and Psychophysics*, 19, 473-483.
- Davies, D. R. & Parasuraman, R. (1982). *The Psychology of Vigilance*. London: Academic Press.

- Doran, S. M., Van Dongen, H. P., & Dinges, D. F. (2001). Sustained attention performance during sleep deprivation: evidence of state instability. *Archives of Italian Biology: Neuroscience* 139(3), 253-267.
- Giambra, L. & Quilter (1987). A two-term exponential functional description of the time course of sustained attention. *Human Factors*, 29, 6, 635-643.
- Gunzelmann, G., Gross, J. B., Gluck, K. A., & Dinges, D. F. (2009). Sleep deprivation and sustained attention performance: Integrating mathematical and cognitive modeling. *Cognitive Science*, 33(5), 880-910.
- Gunzelmann, G. Gluck, K. A., Moore, R., Dinges, D. (2012). Diminished access to declarative knowledge with sleep deprivation. *Cognitive Systems Research*, 13, 1-11.
- Gunzelmann, G., Moore, R. L., Gluck, K., Van Dongen, H. P. A., & Dinges, D. F. (2010). Fatigue in sustained attention: Generalizing mechanisms for time awake to time on task. In P.L Ackerman (Ed.), *Cognitive Fatigue: Multidisciplinary Perspective on Current Research and Future Applications* (pp. 83-96). Washington, DC: American Psychological Association
- Harris, J. Maximizing the utility of MindModeling@Home resources. In Proceedings of The Eleventh World Conference on Integrated Design & Process Technology (IDPT '08), Taichung, Taiwan, 2008.
- Horne, J., & Reyner, L. (1999). Vehicle accidents related to sleep: A review. *Occupational and Environmental Medicine*, 56, 289-294.
- Houk, J. C., & Wise, S. P. (1995). Distributed modular architectures linking basal ganglia, cerebellum, and cerebral cortex: Their role in planning and controlling action. *Cerebral Cortex*, 2, 95-110.
- Jerison, H. J. & Pickett, R. M. (1964). Vigilance: The importance of the elicited observing rate. *Science*, 143, 970-971.
- Khemlani, S., Trafton, J. G. (under review). Percentile analysis for goodness-of-fit comparisons of models to data. In 36th Annual Conference of the Cognitive Science Society.
- Lim, J., Wi, W., Wang, J., Detre, J. A., Dinges, D. F., & Rao, H. (2010). Imaging brain fatigue from sustained mental workload: An ASL perfusion study of the time-on-task effect. *Neuroimaging*, 49, 3426-3435.
- Mackworth, N. H. (1948). The breakdown of vigilance during prolonged visual search. *Quarterly Journal of Experimental Psychology*, vol. 1, pp.6-21
- Mallis, M., Banks, S., & Dinges, D. Sleep and circadian control of neurobehavioral functions. Ed. Parasuraman, R., & Rizzo, M. *Neuroergonomics: The Brain at Work*. New York: Oxford University Press, 2007.
- Mitler, M. M., Carskadon, M. A., Czeisler, C. A., Dement, W. C., Dinges, D. F., & Graeber, R. C. (1988). Catastrophes, sleep, and public policy: Consensus report. *Sleep*, 11(1), 100-109.
- Parasuraman, R., & Davies, D. R. (1977). A taxonomic analysis of vigilance. In R. R. Mackie (Ed.), *Vigilance: Theory, operational performance, and physiological correlates* (pp. 559-574). New York: Plenum.
- Shaw, T.H., Matthews, G., Warm, J.S., Finomore, V.S., Silverman, L., Costa, P.T. (2010). Individual Differences in Vigilance: Personality, Ability and States of Stress. *Journal of Research in Personality*, 44, 297-308.
- Stewart, T.C., Bekolay, T., and Elias Smith, C. (2012) Learning to select actions with spiking neurons in the basal ganglia. *Frontiers in Neuroscience*, 6:2, 1-14.
- Veksler, B. Z., & Gunzelmann, G. (2013). Modeling the Vigilance Decrement in the Mackworth Clock Task. In D. N. Cassenti (Ed.), *Proceedings of the 22nd Annual Conference on Behavior Representation in Modeling and Simulation (BRIMS)*. San Antonio, TX: BRIMS.
- Warm, J. S., & Dember, W. N. (1998). Tests of a vigilance taxonomy. In R.R. Hoffman, M.F. Sherrick, & J.S. Warm (Eds). *Viewing psychology as a whole: The integrative science of William N. Dember* (pp. 87-112). Washington, DC: American Psychological Association.
- Warm, J.S., Parasuraman, R., and Matthews, G., (2008). Vigilance requires hard mental work and is stressful. *Human Factors*, 50, 433-441.
- Warm, J. S., Loeb, M., & Alluisi, E. A. (1970). Variations in watchkeeping performance as a function of the rate and duration of visual signals. *Perception and Psychophysics*, 7, 97-99.
- Wickens, C. D. (1984). Processing resources in attention. In R. Parasuraman & D. R. Davies (Eds.), *Varieties of attention* (pp. 63-102). Orlando, FL: Academic Press.