Requirements for Predicting the Impact of Fatigue on Human Behavior

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Abstract

This paper provides an overview of an approach to developing computational models of fatigue, which has been used to develop detailed accounts of laboratory phenomena, and to make *a priori* predictions in more naturalistic tasks. The research has led to novel theories and mechanisms that help to build bridges between integrated theories of human cognition from cognitive science and theoretical and mathematical research on sleep and fatigue. Moreover, this research lays the foundation for new technologies to help mitigate fatigue risk in applied settings.

Keywords: Sleep; Circadian Rhythm; Prediction; Integrated Theory; Fatigue

Introduction

This paper describes research conducted by me and my collaborators to develop computational mechanisms to account for the impact of sleep loss and circadian rhythms on human cognition. We have described novel theories to explain the influence of these factors (e.g., Gunzelmann, Gluck, Moore, & Dinges, 2012; Gunzelmann, Gross, Gluck, & Dinges, 2009), and have presented models that make *a priori* predictions of performance both in laboratory tasks (Gunzelmann, Byrne, Gluck, & Moore, 2009), and in more naturalistic task contexts (e.g., Gunzelmann & Gluck, 2009; Gunzelmann, Moore, Salvucci, & Gluck, 2011). In addition, we have proposed a set of requirements for creating theories that are useful for making task-specific predictions about the impact of sleep loss that are useful in applied settings (Table 1; Gunzelmann et al., 2011; Jackson et al., 2013).

Table 1. Requirements for making task-specific predictions about performance degradations associated with sleep loss.

	Requirements
1	A quantitative theory of the components of cognition and their interactions
2	An understanding of how the components of cognition are engaged in the performance of a particular task
3	A model of the temporal dynamics of sleep loss and circadian rhythms
4	Mechanisms to explain how the temporal dynamics of fatigue affect specific information processing mechanisms

Requirements for Predicting the Impact of Sleep Loss on Cognitive Behavior

Research on sleep loss and fatigue is important for both theoretical and practical reasons. In theoretical terms, sleep and circadian rhythms are fundamental aspects of human experience, and have well-established impacts on cognitive performance. In practical terms, fatigue creates risk in many real-world contexts, and the consequences of fatigue-related errors and accidents are staggering. As a result, understanding the effects of sleep and circadian rhythms on the human cognitive system is a fundamental challenge for cognitive science, while the ability to accurately predict those effects would have substantial applied benefits. These are challenges addressed in this research by satisfying the requirements listed in Table 1, and discussed in this section.

Requirement #1: A Quantitative Theory of the Components of Cognition

This requirement is satisfied by using the Adaptive Control of Thought – Rational (ACT-R) cognitive architecture, an integrated theory of human cognition that has been implemented in software (Anderson, 2007). Through simulation, ACT-R demonstrates a capacity to replicate important aspects of human information processing and behavior. Of course, ACT-R is but one example of an integrative theory, and it would be possible to adapt our mechanisms and integrate them into alternative theories of the human mind. The main points, however, are that having such a theory is necessary for the research we have done, and that using an existing theory strengthens the theoretical foundations and facilitates progress.

Requirement #2: How the Components of Cognition Are Engaged in Task Performance

Developing models to account for human performance is common in cognitive science. In ACT-R and other frameworks and architectures, computational mechanisms and constraints are combined with task knowledge to define a model, which has the capacity to simulate human behavior in a particular task. As the model does the task, it produces behavioral traces that can be compared directly to human performance data from the same task. However, models also produce traces of the information processing activity that generated the performance data. So, to the extent that a model's behavior corresponds to human performance, it is possible to make assertions about how different components of the cognitive system are engaged in task performance.

Requirement #3: Temporal Dynamics of Sleep Loss and Circadian Rhythms

It is well established that sleep deprivation leads to impaired performance across a broad range of tasks in basic and applied domains (e.g., Goel, Rao, Durmer, & Dinges, 2005). A major focus of the field has been on developing tools to reduce the risk of errors and accidents in applied settings, in addition to understanding how and why such errors occur.

Mathematical models have been developed to address these issues (e.g., McCauley et al., 2009). These models produce an estimate of cognitive functioning, or *alertness*, which represents the interacting influences of the sleep and circadian systems on overall cognition performance.

Requirement #4: Temporal Dynamics Linked to Specific Information Processing Mechanisms

Models developed in ACT-R rely on the coordinated interaction of multiple modules to produce behavior in particular task contexts. Thus, to understand how cognition and behavior will change in a task under the pressure of cognitive moderators like decreased alertness, it is necessary to understand how the efficiency and effectiveness of the information processing in each of the components will be altered as a result of the overall fluctuations in the cognitive system. This has been the focus of our research, leading to quantitative mechanisms that specify the relationships between alertness and cognitive activity and performance.

Conclusion

The research described here has produced theories that explain the impact of sleep loss and circadian rhythms on cognitive performance. A critical theme is the extent to which existing theories have been leveraged to implement more integrated and comprehensive accounts of the influence of the sleep and circadian systems on human performance. This demonstrates how cognitive science can cumulate to provide more detailed and comprehensive accounts of human cognition and behavior.

At a theoretical level, the contributions serve to extend existing integrated theories of human cognition, and to provide more detailed accounts of the relationship between fatigue and cognitive performance. Mechanisms have been proposed for procedural knowledge selection and execution (e.g., Gunzelmann, Gross, et al., 2009), including individual differences (Gunzelmann, Moore, Gluck, Van Dongen, & Dinges, 2009) and time on task effects (Gunzelmann, Moore, Gluck, Van Dongen, & Dinges, 2010). We have also studied the effects of sleep deprivation on the use of previously acquired declarative knowledge (Gunzelmann et al., 2012) and the acquisition of new declarative knowledge (Halverson, Gunzelmann, Moore, & Van Dongen, 2010).

From a practical perspective, we have shown the capacity to use the mechanisms to make *a priori* predictions in novel tasks, ranging from simple dual-task contexts (Gunzelmann, Byrne, et al., 2009) to driving (Gunzelmann et al., 2011) and flying (Gunzelmann & Gluck, 2009). Collectively, this research answers questions about the impact of sleep loss on different components of cognition, and illustrates how to predict changes in real-world behavior.

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References

Anderson, J. R. (2007). *How can the human mind occur in the physical universe?* New York: Oxford University Press.

Goel, N., Rao, H., Durmer, J. S., & Dinges, D. F. (2005). Neurocognitive consequences of sleep deprivation. *Seminars in Neurology*, *25(1)*, 320–339.

Gunzelmann, G., Byrne, M. D., Gluck, K. A., & Moore, L. R. (2009). Using computational cognitive modeling to predict dual-task performance with sleep deprivation. *Human Factors*, *51(2)*, 251-260.

Gunzelmann, G., & Gluck, K. A. (2009). An Integrative approach to understanding and predicting the consequences of fatigue on cognitive performance. *Cognitive Technology, 14(1)*, 14-25.

Gunzelmann, G., Gluck, K. A., Moore, L. R., & Dinges, D. F. (2012). Diminished access to declarative knowledge with sleep deprivation. *Cognitive Systems Research, 13(1)*, 1-11.

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., Moore, L. R., Gluck, K. A., Van Dongen, H. P. A., & Dinges, D. F. (2009). Examining sources of individual variation in sustained attention. In N. Taatgen, & H. van Rijn (Eds.), *Proceedings of the Thirty-First Annual Meeting of the Cognitive Science Society* (pp. 608-613). Austin, TX: Cognitive Science Society.

Gunzelmann, G., Moore, L. R., Gluck, K. A., 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 Perspectives on Current Research and Future Applications* (pp. 83-96). Washington, DC: American Psychological Association.

Gunzelmann, G., Moore, L. R., Salvucci, D. D., & Gluck, K. A. (2011). Sleep loss and driver performance: Quantitative predictions with zero free parameters. *Cognitive Systems Research, 12(2)*, 154-163.

Halverson, T., Gunzelmann, G., Moore, L. R., & Van Dongen, H. P. A. (2010). Modeling the effects of work shift on learning in a mental orientation and rotation task. In D. D. Salvucci & G. Gunzelmann (Eds.), *Proceedings of the 10th International Conference on Cognitive Modeling* (pp. 79-84). Philadelphia, PA: Drexel University.

Jackson, M. L., Gunzelmann, G., Whitney, P., Hinson, J. M., Belenky, G., Rabat, A., & Van Dongen, H. P. A. (2013). Deconstructing and reconstructing cognitive performance in sleep deprivation. *Sleep Medicine Reviews*, *17*, 215-225.

McCauley, P., Kalachev, L. V, Smith, A. D., Belenky, G., Dinges, D. F., & Van Dongen, H. P. A. (2009). A new mathematical model for the homeostatic effects of sleep loss on neurobehavioral performance. *Journal of Theoretical Biology*, *256(2)*, 227–239.