Computational Modeling of Human Multiple-Task Performance and Mental Workload

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13. ABSTRACT ***(Maximum 200 Words)***

This report summarizes the results of an extended project in which a computational modeling system for human cognition and performance, named EPIC (Executive-Process/Interactive Control) was developed, applied to several types of tasks to accurately represent human performance, and inspired to collection of new data that cast new light on the scientific analysis of key phenomena in human performance and cognition. The report summarizes the accomplishments of the project, and includes a complete list of publications and presentations of the project work.

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Computational Modeling of

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Introduction

This was a complex and long-term project, which is still underway under continuing funding that was placed under a new grant for administrative purposes. The purpose of this final report is to summarize the results under the previous funding. The report is organized as follows. Section 1 summarizes the accomplishments of the project, organized in terms of the lines of work, with a few representative publications listed for each line of work. Details of the work, and references to related work in the scientific literature have not been included because this detail is available from the publications themselves. The first section concludes with a statistical summary of the graduate students supported during the project.

Section 2 provides a list of all the publications, presentations, and dissertations produced during the project, organized by type.

Section 1. Summary of Project Accomplishments

Goals of the Project

1. The first goal of the project was to develop a *predictive and explanatory computational theory of human cognition and performance*. This theory was stated in the form of a computational cognitive architecture, named EPIC for Executive-Process Interactive Control. The architecture represents the fixed human abilities and limitations as a collection of processors and memory stores that represent the separate perceptual and motor modalities along with cognitive processing. The cognitive processor is "programmed" with a set of task-specific production rules that represents the human's strategy for perfoming that specific task. Hence performance in a specific situation is a function of both the fixed capabilities represented in the architecture, and the flexible, adaptable strategy executed by the architecture for performing the task. Such a theory would codify the existing scientific knowledge of human cognition and performance into a single coherent framework. At the time the project began, there were a few computational cognitive architectures, but none included perceptual-motor factors, and a few practically-oriented modeling systems that included perceptual-motor factors in an ad-hoc way, but lacked modern representations of cognitive processing. A fundamental and widely influential contribution of this project was to demonstrate that this unification of performance and cognition into a single architecture was both feasible and extremely valuable.

2. A second goal was to *explain multiple-task performance,* in which distinct tasks must be simultaneously executed by humans, and to executive processes, which have been assumed to control or supervise task performance, especially in multitask situations. The fundamental puzzle in this domain is that people do indeed appear to be capable of performing more than one task at a time, but there is a very complex pattern of exactly when they can and cannot do this. Prior to this project, psychological theories of multiple-task performance and executive processes were very vaguely stated, with considerable "hand waving" and no ability to predict or explain the very complex patterns of observed phenomena. The computational cognitive architectures developing at the time could not address these phenomena either, because the effects are very closely tied to the details of the perceptual and motor processing taking place, and the extant architectures did not represent these processes at all, or not well enough, to engage the phenomena. The EPIC architecture exerted a wide influence as the first rigorous presentation of the possible nature of executive processes and how multiple-task performance can be organized.

3. A third goal was to *support a simulation-based design methodology for human-machine systems*, by making the new computational cognitive architecture accurate and practical enough to simulate humans in a simulation-based system design methodology. A simulation could be constructed in which a simulated human interacts with an actual or simulated machine (e.g. a computer-based system) to accomplish tasks. The simulation predicts the performance of the human-machine system. Alternative designs for the machine, or for the human's procedures to operate the machine, can be compared, and the best alternative chosen for future development or training. While actually carrying out this demonstration with a practical design project was beyond the scope of this project, the EPIC architecture provided the foundations for a lower-fidelity simplified cognitive architecture, called GLEAN, for GOMS modeling that is simple and powerful enough to be applied to the analysis of team performance in complex tasks.

To accomplish these goals, the project involved considerable software development of the cognitive architecture for modeling, modeling of previously published data, and the collection of new data, both to support modeling of important phenomena and to demonstrate phenomena predicted by the modeling work. This new data has also provoked considerable interest in the experimental psychology field, as its basis in the cognitive architecture resulted in the demonstration of striking results that defied the conventional wisdom in key areas.

Lines of Work

The EPIC Simulation Software

The software for constructing cognitive-architectural models was originally developed in LISP, and was made available to others for several years at (ftp://www.eecs.umich.edu/people/kieras). The LISP version was used by several other modelers, either directly, as in a combination of SOAR and EPIC, or as the basis for extensions to other architectures, as is the case for ACT-R/PM, and the current ACT-R 5.

A major effort was to completely redesign and rebuild the EPIC software in C++ for better performance, interoperability, and familiarity. In the process, the structure of the software was considerably improved so that the relationship between the software architecture and the psychological architecture was made much more explicit. This version has been in use for the last year.

Modeling Dual Task Performance

Fundamental dual-tasks. The first work undertaken in the project was to account for performance in the Psychological Refractory Period (PRP) task, the simplest possible dual task. In this task, the person performs two overlapping choice reaction tasks. A choice reaction task is simply making one of a set of designated responses to one of a set of stimuli. In the PRP task, two separate choice reaction tasks must be performed, with the two stimuli appearing successively separated by a delay (e.g. 100 ms). Typically, the human is instructed to respond to the first stimulus before responding to the second. The basic phenomenon is that the second response is delayed compared to the time required to perform the second task in isolation, the amount of the response delay increases as the delay between the two stimuli decreases. The effect was widely interpreted as meaning that the human's cognitive processing could make only one response choice at a time, and required some time to recover before it could make another - hence the "refractory period," also characterized as a "central cognitive bottleneck." We chose this as the first line of work reasoning that since the PRP task was the simplest possible dual task, the theory should be able to explain it if it was going to be capable of explaining more complex dual task phenomena.

Our work on the PRP task bore considerable fruit, leading to the discovery that the PRP effect itself was due to a combination of strategy choice made by the human in response to the task demands, and the perceptual-motor constraints due to the combination of stimulus and response modalities, not a "hard-wired" cognitive limitation. This lead further to a clear characterization of executive processes that supervise to the two separate tasks, resulting in the first rigorous theory of executive processes. The greater theoretical clarity lead us to demonstrate empirically the phenomenon of "virtually perfect timesharing" in which humans can do two tasks simultaneously with performance just as good as doing the tasks separately. We were able to characterize the conditions under which such high performance would appear, such as proper training. The individual differences in this ability are striking as well, with implications for personnel selection. The result was an overturning of the "cognitive bottleneck" hypothesis and greater attention to task demands and training that affects strategy choices. Key publications on this line of work are:

Meyer, D. E., & Kieras, D. E. (1997). A computational theory of executive cognitive processes and multiple-task performance: Part 1. Basic mechanisms. *Psychological Review*, 1997, *104*, 3-65.

Meyer, D. E., & Kieras, D. E. (1997). A computational theory of executive cognitive processes and multiple-task performance: Part 2. Accounts of psychological refractory-period phenomena. *Psychological Review*, 1997, *104*, 749-791.

Schumacher, E. H., Lauber, E. J., Glass, J. M. B., Zurbriggen, E. L., Gmeindl, L., Kieras, D. E., & Meyer, D. E. (1999). Concurrent response-selection processes in dual-task performance: Evidence for adaptive executive control of task scheduling. *Journal of Experimental Psychology: Human Perception and Performance*, 1999, *25*, 791-814.

Schumacher, E. H., Seymour, T. L., Glass, J. M., Fencsik, D., Lauber, E. J., Kieras, D. E., & Meyer, D. E. (2001). Virtually perfect time-sharing in dual-task performance: Uncorking the central cognitive bottleneck. *Psychological Science*, 2001, *12*, 101-108.

Complex dual-tasks. While the PRP task was very instructive, there was another category of dual tasks in which there was a more challenging combination of perceptual-motor and cognitive-strategic issues. We chose as a representative an experiment reported by Martin-Emerson & Wickens, which has since been also modeled by other cognitive modelers as a result of our work. In this task, the human must perform continuously a compensatory tracking task, using a right-hand joystick to keep a cursor centered on a stationary target in spite of perturbations applied to it. Concurrently, a visual choice reaction stimulus appears on the display, separated by varying

distances from the stationary target. The human must respond to the choice stimulus by pressing buttons with the left hand. The choice stimulus is small, so if it appears a long distance away, the human must move his/her eyes away from the tracking task to the stimulus in order two discriminate it for the choice response. The reaction time for the choice response and the tracking error increase in interesting ways as the distance between the choice stimulus and tracking target increase. We were able to model this task successfully, incorporating a simple but apparently adequate model for continuous tracking, and a model for eye movement and perceptual recognition time based on results in the literature. However, the interesting insight was that the model required a highly-optimized executive process that would suspend the tracking task for the absolute minimum amount of time required to move the eye to the choice stimulus and back to the tracking stimulus. In other words, the two tasks were being executed in a highly overlapped mode, rather than sequentially, showing yet another example of highly parallelized cognitive processing, as in the PRP task. In later theoretical work, we explored a large variety of different executive processes for this task. This work was not the subject of a single publication, but some relevant publications that made use of it are:

A second complex dual task was also a focus of user-interface analysis work. This task and its experimental data were developed by James Ballas and his coworkers at the Naval Research Laboratory to resemble actual military aircraft cockpit tasks. In one display, the human had to perform a pursuit tracking task with a right-hand joystick. Simultaneously, in a second display, a simplified radar display showed "blips" that moved down the screen towards "ownship." The blips had to be classified as hostile or friendly depending on details of their motion. The human could perform the classification and enter it manually on a keypad or a touch screen, depending on which version of the interface they were using. However, a simulated cockpit automation system could also perform the classification automatically, leaving the human free to perform the tracking task. The automated system would disengage from time to time, and leave the human to do both tasks unaided. The basic effect was an "automation deficit" effect in which for a period of time after having to resume the formerly automated task, it took the human longer to respond to the blips than compared to the same types of events during steady-state performance. Interestingly, the touch-screen interface showed a substantially smaller automation deficit, although the it was not faster overall than the keypad interface.

The details of this effect, and how it depended on the interface, could be explained by EPIC models in which there was heavy interaction between executive processes, eye movement control, and manual movement programming. The classification task display was ignored during automated execution. When the classification task had to be resumed, the executive process overlapped the phases of the target classification task, and adapted the extent of the overlapping to the workload demands of the task. When in steady state, the executive would start the classification task immediately for a blip, or even anticipate it. But during the "catch up" phase of the newly-resumed task, several blips that were already present, so there would be a delay in starting the first one, and they might even be handled out of order. During high workload, when several blips were present, the model worked harder by overlapping more processes, compared to low workload. The two interfaces produced different effects simply because the differed in the details of when eye movements could be made, which in turn governed how much the task processes could be overlapped. The lessons learned from this modeling work were further demonstration of the potential for large-scale parallelism of perceptual-motor and cognitive processes, and the key role played by task strategies, and how the strategy could modify performance during real time. In addition, the EPIC architecture was shown to be capable of accounting for the details of task performance in situations that began to have some resemblance to actual military tasks. Some representative publications of this work are:

Ballas, J.R., Kieras, D.E., Meyer, D.E., Stroup, J., & Brock, D. (1999) How is tracking affected by actions on another task? In *Proceedings of the Tenth Aviation Psychology Symposium*, Columbus, Ohio, May 3-6, 1999.

Kieras, D. E., & Meyer, D. E. (1995). Predicting human performance in dual-task tracking and decision making with computational models using the EPIC architecture. In D. S. Alberts, D. Buede, T. Clark, R. Hayes, J. Hofmann, W. Round, S. Starr, & W. Vaughan (Eds.), *Proceedings of The International Symposium on Command and Control Research and Technology* (pp. 314-325). Washington, DC: National Defense University, 1995.

Meyer, D. E., & Kieras, D. E. (1999). Précis to a practical unified theory of cognition and action: Some lessons from computational modeling of human multiple-task performance. In D. Gopher & A. Koriat (Eds.), *Attention and performance XVII* (pp. 17-88). Cambridge, MA: M.I.T. Press, 1999.

Kieras, D. E., Meyer, D. E., Ballas, J. A., & Lauber, E. J. (2000). Modern computational perspectives on executive mental control: Where to from here? In S. Monsell & J. Driver (Eds.), *Control of cognitive processes: Attention and performance XVIII* (pp. 681-712). Cambridge, MA: M.I.T. Press, 2000.

Working Memory

Extending the reported research on multitasking, a complementary line of investigation in this project has focused on human working memory. By definition, working memory involves the temporary storage, maintenance, and updating of intermediate products from information processing for "situation awareness" during task performance. Multitasking depends crucially on several types of working memory, including on-line storage systems for visual information, verbal information, and abstract information that serves to regulate the flow of control through various processing stages. For each of these cases, concerted efforts have been made in this project to discover the fundamental empirical properties of human working memory, incorporate them properly in components of the present computational cognitive architecture, and formulate accurate computational models of multitasking that rely significantly on this implementation.

Visual Working Memory. With respect to visual working memory, our experiments have used a visual change-detection task. During this task, observers have to judge whether displayed arrays of visual objects (e.g., colored icons with various shapes) are "same" or "different" compared to brief preceding arrays. Results concerning the speed and accuracy of such judgments provide evidence about the capacity, duration, and forms of information coding in several subtypes of visual working-memory stores.

On the basis of results from several versions of the visual change-detection task, we have formulated and tested a rigorous quantitative model that makes precise theoretical assumptions about the basic properties of human visual working memory. According to this model, specific bits of information about individual objects in a displayed array are stored in "object files", which combine the perceptual features (e.g., shape, size, and color) of each object in an integrated packet. Our results indicate that people have approximately three object files available for storage of information about objects from a recent visual display that persists for a fairly long time.

Some representative publications of this work are:

Fencsik, D. E., Seymour, T. L., Mueller, S. T., Kieras, D. E., & Meyer, D. E. (2002). *Representation, retention, and recognition of information in visual working memory.* Poster presented at the meeting of the Psychonomic Society, Kansas City, MO, November, 2002.

Fencsik, D. *Representation and processing of objects and object features in visual working memory.* Doctoral Dissertation, Department of Psychology, University of Michigan, 2003.

Verbal working memory. In actual tasks, verbal information over short to intermediate periods of time (≤ 1 min) must often be retained. Hence, along with investigating human visual working memory, this project has pursued detailed empirical and theoretical studies of verbal working memory (i.e., the temporary storage of auditory signals and speech) during on-line vocal information processing. Our research has dealt especially with the performance of basic tasks that engage fundamental verbal working-memory mechanisms. For example, one such task whose results have occupied us extensively involves verbal serial recall. In this task, as in many practical situations, a performer receives a short sequence spoken words and then has to repeat them immediately afterwards in the same order as they were originally received. The percentages of correctly recalled sequences are measured as a function of the sequence length (i.e., number of presented words) and other factors (e.g., the articulatory durations of the words and their phonological similarities to each other).

To account for results from these measurements, and to discover more about verbal working memory, EPIC computational models that implement a "rehearsal loop" have been formulated. Our models use a combination of EPIC components, which include the architecture's auditory perceptual processor, working-memory store for phonological speech codes, and vocal motor processor for generating covert and overt articulatory outputs. So that a rehearsal loop can be implemented with these components, a direct link between the vocal motor processor and auditory perceptual processor was added to EPIC. This link enables covert articulatory codes produced by the vocal motor processor to enter the auditory perceptual processor and be recoded for storage in phonological working memory. Also, our models rely on multiple complementary sets of production rules that respectively enable construction of word chains from spoken inputs, intermediate cyclic rehearsal of these chains, and final overt serial recall. With these mechanisms and production-rule sets, our models of verbal working memory yield simulated recall-accuracy data that closely approximate empirical results from the verbal serial recall task.

Modeling of performance in the serial recall task has provided several deep insights about verbal working memory. We have found that to be performed properly, even this relatively basic task requires rather elaborate executive control processes. They are needed to supervise the "bookkeeping" and "memory updating" for concurrent word input, rehearsal, and recall. The complexity of the required supervision is much greater than previous theorists have appreciated, and it must be accommodated in more detail as part of veridical models for verbal working memory. Likewise important is our discovery that in order to have a viable rehearsal loop, the lifetimes of covert phonological codes for spoken words must be much longer (viz., on the order of 10 sec) than some previous theorists have assumed.

To bolster the empirical foundations for our computational modeling of performance in serial recall and other verbal working memory tasks, we have also developed principled new methods for measuring the phonological similarities and articulatory durations of words in memorized sequences. Our methods constitute a significant advance over other extant ones in the literature, which suffer from serious flaws that have precipitated numerous debates about the nature of verbal working memory. We measure phonological similarity quantitatively through a formal metric. This metric assumes that the phonological similarity between paired words is represented as a multidimensional vector of psychologically relevant aspects of similarity, which constitute a *similarity profile.* The individual dimensions of this profile include various quantities, such as the degree to which the words rhyme, the degree to which their syllable onsets match or mismatch, and the amount of concordance between their stress patterns. Unlike other measures of similarity using

in working memory research, ours have a rigorous theoretical basis and are sensitive to fundamental characteristics of speech that are relevant for serial recall. We have succeeded at resolving a number of prevailing theoretical and empirical controversies about the nature of verbal working memory.

Some representative publications of this work are:

Kieras, D.E., Meyer, D.E., Mueller, S., & Seymour, T. (1999). Insights into working memory from the perspective of the EPIC architecture for modeling skilled perceptual-motor and cognitive human performance. In A. Miyake and P. Shah (Eds.), *Models of Working Memory: Mechanisms of Active Maintenance and Executive Control.* New York: Cambridge University Press. 183-223.

Mueller, S. T., Seymour, T. L., Kieras, D. E., & Meyer, D. E. (2002). Theoretical implications of articulatory duration, phonological similarity, and phonological complexity effects in verbal working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, in press.

Mueller, S. T. *The roles of cognitive architecture and recall strategies in performance of the immediate serial recall task.* Doctoral Dissertation, Department of Psychology, University of Michigan, 2002.

Application to user interface analysis

One of the goals of the project was to be able to contribute to practical issues, in particular how system user interfaces should be designed to maximize human ability to perform complex tasks. The basic rationale for the approach is that a model of human performance can serve as a simulated user of a new system that is being designed. By setting up a simulated user to interact with a simulated system design, one can obtain measures of performance of the human-machine system without have to construct expensive and labor-intensive mockup or prototype versions of the system, which conventional user testing methodology requires. In this project, the main thrust was to demonstrate and explore the ability of the EPIC architecture to contribute to such analyses. Other related work described in the transitions section below concerns using a simplified version of the EPIC architecture for practical user interface analysis. An introductory publication on the relevance of EPIC to user interface problems appears in:

Kieras, D. E., & Meyer, D. E. (1997). An overview of the EPIC architecture for cognition and performance with application to human-computer interaction. *Human-Computer Interaction*, 1997, *12*, 391-438.

High-performance multimodal tasks. A distinctive feature of EPIC is the ability to represent the time course involved in perceptual and motor processing, and how they can overlap with each other and cognitive processing. The first human-computer interaction project attempted with EPIC was to model the telephone operator task that had been previously model in a more limited, ad-hoc way by other researchers using a non-simulation approach based on PERT chart analysis. This work was done in conjunction with support from the former NYNEX corporation. Telephone operators work in multimodal tasks whose time cost can be quite significant when taken over the total call volume. The original research had demonstrated that an analysis could identify a second's worth of time savings per task that would add up to millions of dollars per year. Our goal was to simply show that EPIC models could capture the same phenomena using a more a-priori and thus even less expensive form of analysis. In addition, it was important to discover how highly practiced users would conduct the task - they had years of practice, and the architecture incorporated many possible

ways in which the task could be performed efficiently. By careful study of these highly practiced users, perhaps we could determined some of the nature of the effects of considerable experience.

We started with a simple task-analytic model of the task, and systematically represented as EPIC production rules the strategy for doing the task. This involved auditory-vocal interaction with the customer, and visual-manual interaction with the workstation. Different levels of efficiency were systematically represented in terms of the policy in which the production rules overlapped different parts of the task. The basic result of this work was that a model with a very simple overlapping policy predicted the task execution times very well, in fact considerably more robustly than the very labor-intensive and ad-hoc models originally constructed for this data. The EPIC model also explained in detail the pattern of manual digit entry timings in which auditory input from the customer's reciting a telephone number was "buffered" and used to control the hand over an extended period of time. Thus constructing an EPIC model of a multimodal task was demonstrated to be a viable and potential useful way to predict human performance in a reasonably complex task. The representative publication for this work is:

Kieras, D.E., Wood, S.D., & Meyer, D.E. (1997). Predictive engineering models based on the EPIC architecture for a multimodal high-performance human-computer interaction task. *ACM Transactions on Computer-Human Interaction.* **4**, 230-275.

Visual search of computer menus. Another line of work that exploited EPIC's ability to overlap cognitive, perceptual, and motor operators was pursued by Anthony Hornof as his dissertation work. Although computer menus are a ubiquitous part of current user interfaces, theoretical work on understanding how they worked in fundamental human processing terms was lacking. The problem is how a user would search a menu for a desired item and then select the proper one by clicking on it. The conventional wisdom was that a user would examine each item and decide whether it was the desired item, and then if so, move the mouse to it. A common result appearing in the literature was that the search was approximately linear with the position of the sought-for item on the menu, with a slope of about 100 ms/item. On the basis of casual evidence, some researchers had proposed that the user is likely to move the mouse from item to item along the way. However, a simple application of the processor times included in EPIC shows that there is no way the observed search rate could be obtained with such a process - the slope would be far larger. Hornof proposed a model in which the eye was sent scanning down the menu as rapidly as possible, with a parallel process that watched for a match to the sought-for item, and then sent the eye and the mouse pointing to the item. This model was still quite simple, but immediately could account for the fast search rate. Hornof went on to show that the model could also account for a subtle mix of effects produced by overall menu length and item position. A key aspect of the model was that more than one menu item could be visually recognized at a given eye position, an assumption that was subsequently found to agree with a variety of results in the other visual search literature. Furthermore, Hornof was able to generalize to other menu arrangements, where the item position could be predicted (e.g. the items were in order), and even two-dimensional menus with effects produced by grouping and group labels. This work was a prime demonstration of the value of modeling for human-computer interaction research: A basic component of human-computer interaction involved complex parallel processing involving fundamentals of the human visual and motor systems. Additionally, it provided valuable confirmation of the basis approach taken in EPIC. Some representative publications of this work are:

Hornof, A. J. *Computational models of the perceptual, cognitive, and motor processes involved in the visual search of pull-down menus and computer screens.* Doctoral Dissertation, Department of Electrical Engineering and Computer Science, University of Michigan, 1999.

Hornof, A. J. & Kieras, D. E. (1997). Cognitive modeling reveals menu search is both random and systematic. *Proceedings of the CHI'97 Conference on Human Factors in Computing Systems*, 107-114. New York: ACM.

Hornof, A. J., & Kieras, D. E. (1999). Cognitive modeling demonstrates how people use anticipated location knowledge of menu items. *Proceedings of CHI 99*, New York: ACM.

Task analysis and modeling methodology. An early insight from the PRP modeling work with EPIC was the discovery that the level of performance in even an extremely simple task depending on the task strategy adopted by the human, and there were hitherto unsuspected ways in which the strategy could differ - basically the efficiency with which the human overlapped the perceptual, cognitive, and motor processes could be varied over a wide range and still be in conformity with the basic task requirements and instructions. In a wider perspective, it meant that absolute levels of task performance in practical situations (such as the use of a CIC interface) could not be predicted, since in general it could not be determined what level of task optimization the human would indulge in, and this decision on their part would have a substantial effect on the total human-system performance. Furthermore, being able to predict task performance is a key rationale for the development of models of human performance. Note that the conventional logic of constructing a model and then validating it against data can not be done when a system is being designed; because the system does not yet exist, it is not possible to collect any data on actual human performance with it to calibrate the model - to be of value in system design, the model must yield useful predictions without requiring a version of the system to be built and tried with humans.

A solution we developed was bracketing logic: Instead of trying to predict in advance exactly which strategy the future user of a system would adopt, instead we could construct two models: one performed the task as rapidly and as efficiently as possible - the fastest-possible model The other model would conform to the task requirements, but not include an attempts to overlap processing in any strategic way - the slowest-reasonable model. The fastest-possible model basically reveals the cognitive-architectural limits on performance of the specified system; the slowest-possible model reveals the task structure implied by the specified system. These two models should bracket the actual human's performance. A series of applications of the logic to the Ballas task, both old and new data, showed that the bracketing could indeed be done on an a-priori basis. But more generally, bracketing has become something of a standard concept of how predictive models of human performance can be used in a system design setting. Some representative publications on this topic are:

Kieras, D. E., & Meyer, D. E. (2000). The role of cognitive task analysis in the application of predictive models of human performance. In J. M. C. Schraagen, S. E. Chipman, & V. L. Shalin (Eds.), *Cognitive task analysis*. Mahwah, NJ: Lawrence Erlbaum, 2000.

Kieras, D.E. Model-based evaluation (2003). In J. Jacko & A. Sears(Eds.), *The Human-Computer Interaction Handbook*. Mahwah, New Jersey: Lawrence Erlbaum Associates. 1139-1151.

Related project: Auditory cueing in dual task performance. An extension to the Ballas project was supported by some supplementary funding, but made heavy use of the EPIC architecture and software, and resulted in some important extensions and modifications. Some previous research in the literature suggested that visual attention could be "steered" by auditory events to the proper point in space. Thus the research question was whether the automation deficit discovered in the original experiments could be alleviated by using localized sound to direct the operator's attention to the most relevant or important "blip" when the task had to be resumed. A localized sound synthesizer was used to produce a sound that represented the type of blip and that appeared to be

coming from the same spatial location as the blip. For this project, the concern was with how spatial properties of sound should be associated with the spatial location of visual objects. The architecture was extended to include this association, and then bracketing methodology was used to rapidly determine how the relation between auditory and visual spatial information could be used to improve performance in the task. The empirical effects showed a small, but general, benefit of the use of localized auditory cues, which was not specific to the automation deficit situation. The modeling showed that this effect could not be attributed the sound being used strategically, to decide what to look at. Instead, the sound onset appeared to produce a reflexive eye movement - an orienting reflex - to take the eyes directly to appropriate object. By adding this pathway to the EPIC architecture, it was possible to account for both the quantitative size of the effect and its qualitative uniformity. Representative publications about this work are:

Ballas J. A., Kieras, D. E. & Meyer, D. E. (1996). Computational modeling of multimodal I/O in simulated cockpits. In S. P. Frysinger & G. Kramer (Eds.) In *Proceedings of the Third International Conference on Auditory Display.* Xerox Palo Alto Research Center, Palo Alto, CA, Nov. 4-6, 1996, pp 135-136.

Ballas, J., Brock, D. Stroup, J. Kieras, D. and Meyer, D. (1999) Cueing of Display Objects by 3-D Audio to Reduce Automation Deficit. In *Proceedings of the Fourth Annual Symposium and Exhibition on Situational Awareness in the Tactical Air Environment.* The Naval Air Warfare Center, Patuxent River, MD, June 8-9, 1999, pp 100-110.

Kieras, D.E., Ballas, J.A., & Meyer, D.E. Computational models for the effects of localized sound cueing in a complex dual task. (EPIC Tech. Rep. No. 13, TR-01/ONR-EPIC-13). Ann Arbor, University of Michigan, Electrical Engineering and Computer Science Department. January 31, 2001.

Transitions

Cognitive effects of aging. Among the transitions to practical applications that have been initiated as part of the present research project, some deal with essential aspects of personnel selection and training. Specifically, in order to improve personnel selection and training, individual differences among people's abilities and skills at cognitive information processing and perceptual-motor task performance must be properly characterized and evaluated. Thus, using concepts based on the EPIC computational cognitive architecture and theoretical analysis of multitasking, we have begun pursuing such needed characterization and evaluation.

This pursuit started initially with studies of age-related changes in cognitive processes, as revealed through comparing performance by senior (age 65 to 70 years) and young (age 18 to 25 years) adults under circumstances that require multitasking and major contributions of working memory. This particular emphasis stemmed from three considerations: (1) in some key respects, cognitive effects of aging are similar to those that hinder people with deficiencies of "fluid intelligence", one of the primary individual-difference factors; (2) these effects are also similar to those caused by fatigue and sleep deprivation, which have direct relevance to performance under combat conditions; (3) the models of multitasking and working memory that we previously developed in this project provide powerful tools for understanding and interpreting such effects.

Given these considerations, we conducted experiments that measure multitasking performance by both senior and young adults under the classical PRP procedure, which was mentioned previously in this report. Results of these experiments revealed that healthy senior adults respond more slowly than do young adults, and they have especially long reaction times for secondary tasks performed concurrently with primary tasks. However, the dual-task performance of these senior adults was

not found to be deficient in all key respects; rather, like young adults, seniors may accomplish certain stages of information processing (e.g., perceptual encoding of stimuli; selection of responses) simultaneously for multiple tasks. Indeed, analyses of how aging affects cognition and human performance based on the EPIC computational cognitive architecture suggested that these effects may be localized primarily in slowed perceptual encoding processes and secondarily in slightly reduced rates of applying production rules for task procedures. However, the seniors appeared similar to young adults in the task procedures and task-scheduling strategies that they could use successfully. Furthermore, other experiments in related work revealed that the verbal-working memory capacities of healthy senior adults are essentially intact until relatively late in life. Up until then, minor declines of memory-task performance over the life span may stem just from modest age-related slowing of cognitive operations for information rehearsal. Taken overall, this set of informative analyses inspired by the EPIC computational cognitive architecture suggests that it can be applied subsequently to establish beneficial new approaches for assessing individual differences in performance abilities and thereby contributing to the advance of personnel selection and training techniques. Some representative publications of this work are:

Glass, J. M. B., Schumacher, E. H., Lauber, E. J., Zurbriggen, E. L., Gmeindl, L., Kieras, D. E., & Meyer, D. E. (2000). Aging and the psychological refractory period: Task-coordination strategies in young and old adults. *Psychology and Aging*, 2000, *15*, 571-595.

Meyer, D. E., Glass, J. M., Mueller, S. T., Seymour, T. L., & Kieras, D. E. (2001). Executive-process interactive control: A unified computational theory for answering twenty questions (and more) about cognitive aging. *European Journal of Cognitive Psychology*, *13*, 123-164.

Support for system user interface design: Modeling complex team tasks. The EPIC architecture was the inspiration for another system for human performance modeling, known as GLEAN3 (GOMS Language Evaluation and Analysis - version 3). This system is basically a simplified version of the EPIC architecture, and was implemented in C++. The lessons learned there were then applied to the C++ version of EPIC, so there has been considerable cross-fertilization at the level of software implementation. At the level of modeling methodology, there has also been considerable cross-fertilization as well. GOMS methodology with GLEAN3 is a practically-oriented approach to modeling human performance that relies on a programming language of cognitive processing that resembles a conventional programming language, and highly simplified models of human perceptual, motor, and cognitive processors. GLEAN3 surpasses EPIC in that it has direct support for modeling complex team tasks; for example, it is easy to instantiate multiple simulated humans and specify how they interact with each other via speech messages. With GLEAN3 it is fairly easy to construct models of teams of humans doing complex tasks, and do so in a way that has clear connections to the underlying theory of human cognition and performance. GLEAN3 suggests a pathway for a future version of EPIC, in which the full precision of the EPIC architecture will be available, but packaged in a way that is both relatively easy to use and also very general and powerful. A representative publication of this work is:

Santoro, T.P., Kieras, D.E., and Pharmer, J. (in press). Verification and validation of latency and workload predictions for a team of humans by a team of GOMS models. *US Navy Journal of Underwater Acoustics, Special Issue on Modeling and Simulation.*

Kieras. D.E. & Santoro, T.P. (2004). Computational GOMS Modeling of a Complex Team Task: Lessons Learned. In *Proceedings of CHI 2004: Human Factors in Computing Systems.* New York: ACM, Inc.

Graduate Training Statistics

Number of Sponsored Ph. D. Degrees: 10

Doctoral Students -- Minority Women: 1

Doctoral Students -- Non-Minority Women: 2

Doctoral Students -- Minority Men: 1

Doctoral Students -- Non-Minority Men: 6

Section 2. Publications & Presentations

Refereed Journal Articles

Glass, J. M. B., Schumacher, E. H., Lauber, E. J., Zurbriggen, E. L., Gmeindl, L., Kieras, D. E., & Meyer, D. E. (2000). Aging and the psychological refractory period: Task-coordination strategies in young and old adults. *Psychology and Aging*, 2000, *15*, 571-595.

Kieras, D. E., & Meyer, D. E. (1997). An overview of the EPIC architecture for cognition and performance with application to human-computer interaction. *Human-Computer Interaction*, 1997, *12*, 391-438.

Kieras, D. E., Wood, S. D., & Meyer, D. E. (1997) Predictive engineering models based on the EPIC architecture for a multimodal high-performance human-computer interaction task. *ACM Transactions on Computer-Human Interaction*, 1997, *4*, 230-275.

Meyer, D. E., Glass, J. M., Mueller, S. T., Seymour, T. L., & Kieras, D. E. (2001). Executive-process interactive control: A unified computational theory for answering twenty questions (and more) about cognitive aging. *European Journal of Cognitive Psychology*, *13*, 123-164.

Meyer, D. E., Kieras, D. E., Lauber, E., Schumacher, E., Glass, J., Zurbriggen, E., Gmeindl, L., & Apfelblat, D. (1995). Adaptive executive control: Flexible multiple-task performance without pervasive immutable response-selection bottlenecks. *Acta Psychologica*, 1995, *90*, 163-190.

Meyer, D. E., & Kieras, D. E. (1997). A computational theory of executive cognitive processes and multiple-task performance: Part 1. Basic mechanisms. *Psychological Review*, 1997, *104*, 3-65.

Meyer, D. E., & Kieras, D. E. (1997). A computational theory of executive cognitive processes and multiple-task performance: Part 2. Accounts of psychological refractory-period phenomena. *Psychological Review*, 1997, *104*, 749-791.

Mueller, S. T., Seymour, T. L., Kieras, D. E., & Meyer, D. E. (2002). Theoretical implications of articulatory duration, phonological similarity, and phonological complexity effects in verbal working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, in press.

Schumacher, E. H., Lauber, E. J., Glass, J. M. B., Zurbriggen, E. L., Gmeindl, L., Kieras, D. E., & Meyer, D. E. (1999). Concurrent response-selection processes in dual-task performance: Evidence for adaptive executive control of task scheduling. *Journal of Experimental Psychology: Human Perception and Performance*, 1999, *25*, 791-814.

Schumacher, E. H., Seymour, T. L., Glass, J. M., Fencsik, D., Lauber, E. J., Kieras, D. E., & Meyer, D. E. (2001). Virtually perfect time-sharing in dual-task performance: Uncorking the central cognitive bottleneck. *Psychological Science*, 2001, *12*, 101-108.

Book Chapters

Kieras, D.E. Model-based evaluation (2003). In J. Jacko & A. Sears(Eds.), *The Human-Computer Interaction Handbook*. Mahwah, New Jersey: Lawrence Erlbaum Associates. 1139-1151.

Kieras, D. E., & Meyer, D. E. (2000). The role of cognitive task analysis in the application of predictive models of human performance. In J. M. Schraagen, S. F. Chipman, & V. L. Shalin (Eds.), *Cognitive task analysis* (pp. 237-260). Mahwah, NJ: Lawrence Erlbaum, 2000.

Kieras, D. E., Meyer, D. E., Ballas, J. A., & Lauber, E. J. (2000). Modern computational perspectives on executive mental control: Where to from here? In S. Monsell & J. Driver (Eds.), *Control of cognitive processes: Attention and performance XVIII* (pp. 681-712). Cambridge,

MA: M.I.T. Press, 2000.

Kieras, D. E., Meyer, D. E., Mueller, S., & Seymour, T. (1999). Insights into working memory from the perspective of the EPIC architecture for modeling skilled perceptual-motor and cognitive human performance. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 183-223). New York: Cambridge University Press, 1999.

Meyer, D. E., & Kieras, D. E. (1999). Précis to a practical unified theory of cognition and action: Some lessons from computational modeling of human multiple-task performance. In D. Gopher & A. Koriat (Eds.), *Attention and performance XVII* (pp. 17-88). Cambridge, MA: M.I.T. Press, 1999.

Abstracts and Refereed Papers in Published Conference Proceedings

Ballas, J., Brock, D. Stroup, J. Kieras, D. and Meyer, D. (1999) Cueing of Display Objects by 3-D Audio to Reduce Automation Deficit. In *Proceedings of the Fourth Annual Symposium and Exhibition on Situational Awareness in the Tactical Air Environment.* The Naval Air Warfare Center, Patuxent River, MD, June 8-9, 1999, pp 100-110.

Ballas J. A., Kieras, D. E. & Meyer, D. E. (1996). Computational modeling of multimodal I/O in simulated cockpits. In S. P. Frysinger & G. Kramer (Eds.) In *Proceedings of the Third International Conference on Auditory Display.* Xerox Palo Alto Research Center, Palo Alto, CA, Nov. 4-6, 1996, pp 135-136.

Ballas, J.R., Kieras, D.E., Meyer, D.E., Stroup, J., & Brock, D. (1999) How is tracking affected by actions on another task? In *Proceedings of the Tenth Aviation Psychology Symposium,* Columbus, Ohio, May 3-6, 1999.

Hornof, A. J., & Kieras, D. E. (1997). Cognitive modeling reveals menu search is both random and systematic. *Proceedings of CHI '97* (pp. 107-114). New York: ACM, 1997.

Hornof, A. J., & Kieras, D. E. (1999). Cognitive modeling demonstrates how people use anticipated location knowledge of menu items. *Proceedings of CHI 99*, New York: ACM.

Kieras, D. E., & Meyer, D. E. (1995). Predicting human performance in dual-task tracking and decision making with computational models using the EPIC architecture. In D. S. Alberts, D. Buede, T. Clark, R. Hayes, J. Hofmann, W. Round, S. Starr, & W. Vaughan (Eds.), *Proceedings of The International Symposium on Command and Control Research and Technology* (pp. 314-325). Washington, DC: National Defense University, 1995.

Kieras, D. E., Meyer, D. E., & Ballas, J. (2001). Towards demystification of direct manipulation: Cognitive modeling charts the gulf of execution. *Proceedings of The CHI 2001 Conference on Human Factors in Computing Systems* (pp. 128-135). New York: Association of Computing Machinery, 2001.

Kieras, D. E., Wood, S. D., & Meyer, D. E. (1995). Predictive engineering models using the EPIC architecture for a high-performance task. In I. R. Katz, R. Mack, L. Marks, M. B. Rossan, & J. Nielsen (Eds.), *Proceedings of The CHI'95 Conference on Human Factors in Computing Systems* (pp. 11-18). New York: Association of Computing Machinery, 1995.

Meyer, D. E., & Kieras, D. E. (1992). The PRP effect: Central bottleneck, perceptual-motor limitations, or task strategies? (Abstract). *Bulletin of The Psychonomic Society*, 1992, *30.*

Wood, S. D., Kieras, D. E., & Meyer, D. E.(1994). An EPIC model for a high-performance HCI task. In *Proceedings of The CHI'94 Conference on Human Factors in Computing Systems* (pp. 24-28). New York: Association of Computing Machinery, 1994.

Invited Talks

Kieras, D. (1992). Analytic Models in User Interface Design. Presented at the Graphics, Visualization, and Usability Center, College of Computing, Georgia Institute of Technology, Atlanta, January 7, 1992

Kieras, D. (1994). Using computational models of human performance in user interface design. Presented in the Navy Center for Applied Research in Artificial Intelligence Seminar Series, May 9, 1994.

Kieras, D.E. (1997, March). Advanced cognitive models for HCI design. Presented at the APA Division 21 Midyear Science Symposium, Arlington, VA. March 6, 1997.

Kieras, D.E. (1997, September). How can a cognitive architecture be useful for computer system design? Presented at the ONR Cognitive Neuroscience Workshop, Woods Hole, MA, Sept. 4-5, 1997.

Kieras, D.E. (1997, October). The Role of Cognitive Task Analysis in the Application of Predictive Models of Human Performance. Presented at the NATO-ONR Workshop on

Kieras, D.E. (1997, November). Predicting Human Performance by Modeling Procedural Knowledge. Presented at the ONR Workshop on Cognitive Models in the Design and Operation of Complex Systems. November 13-15, 1997, Baltimore.

Kieras, D.E. (1999, September). Basic Concepts of Effective Displays and Interfaces. Invited presentation at the ONR Technical Workshop on Sensor Data Visualization, Naval Undersea Warfare Center, Newport, RI., September 9-10.

Kieras, D.E. (2000, March). Modeling Human Performance for System Design Evaluation. Presented at the Cognitive Science Colloquium series, Georgia Institute of Technology, March 17, 2000.

Kieras, D.E., & Meyer, D.E. (1995, July). An introduction to the EPIC architecture for human cognition and performance modeling. Presented in the Symposium on Production System Models of Complex Cognition, organized by J.R. Anderson, Cognitive Science Society Meeting, Pittsburgh, July 22-25, 1995.

Kieras, D.E., & Meyer, D.E. (1996, June). The EPIC architecture for human cognition and performance modeling. Presented in the ACT-R Workshop, Carnegie-Mellon University, Pittsburgh, June 29, 1996.

Kieras, D. E. & Meyer, D. E. (1992). Computational Modeling of Human Multiple-Task Performance. Presented at the Cognitive Science Colloquium Series, Georgia Institute of Technology, January 8, 1992.

Kieras, D. E., Meyer, D. E., Ballas, J. A., & Lauber, E. J.(1998). *Modern computational perspectives on executive mental control: Where to from here*? Invited paper presented at the Eighteenth International Symposium on Attention and Performance, Windsor, England, July, 1998.

Meyer, D. E. (2002). *New prospects for computational unified theories of cognition and action.* Distinguished Scientific Contribution Award Address presented at the meeting of the American Psychological Association, Chicago, IL, August, 2002.

Meyer, D. E., & Kieras, D. E. (1994, December). EPIC computational models of human multiple-task performance. Paper presented at The Netherlands Royal Academy Conference on Discrete and Continuous Human Information Processing, Amsterdam, The Netherlands.

Meyer, D. E., & Kieras, D. E. (1995, February). Theoretical perspectives on cognitive aging from the viewpoint of the EPIC architecture for computational modeling of human performance. Paper presented at the Southeastern Center Conference on Aging and Skill, Destin, FL.

Meyer, D. E., & Kieras, D. E. (1995, March). EPIC computational models of human performance in elementary and complex task domains. Presented at the Conference on Human Perceptual and Motor Abilities, Brooks AFB, San Antonio, Texas.

Meyer, D. E., & Kieras, D. E. (1996, July). Some lessons from computational modeling of human multiple-task performance. Invited keynote address presented at the 17th International Symposium on Attention and Performance, Haifa, Israel, July, 1996.

Meyer, D. E., & Kieras, D. E. (1999). *Executive-Process Interactive Control (EPIC): A cognitive architecture for comprehensive precise computational modeling of human multiple-task performance in laboratory and real-world contexts.*(1999). Invited address presented at the meeting of the European Society for Cognitive Psychology, Ghent, Belgium, September, 1999.

Meyer, D. E., & Kieras, D. E. (2002). *Toward solutions to unsolved problems in the computational theory of executive cognitive control and multiple-task performance.*(2002). Invited paper presented at the International Symposium on Executive Cognitive Functions, Konstanz, Germany, July, 2002.

Meyer, D. E., & Kieras, D. E. (2002). Toward solutions to unsolved problems in the computational theory of executive cognitive control and multiple-task performance. Invited paper presented in the Symposium on Approaches to Cognitive Control and The Central Executive at the meeting of the Psychonomic Society, Kansas City, MO, November, 2002.

Meyer, D. E., & Kieras, D. E. (2002). Computational approaches to cognitive psychology, cognitive neuroscience, and cognitive aging. Invited lecture presented at the Dartmouth Summer Institute on Cognitive Neuroscience, Hanover, NH.

Meyer, D. E., Kieras, D. E., & Glass, J. M. B.(1999). *Analysis of Components in Cognitive Aging Based on The Executive-Process Interactive Control (EPIC) Architecture for Realistic Computational Modeling of Rapid Complex Human Perceptual-Motor and Cognitive Performance.* Invited paper presented at the International Workshop on Aging and Executive Control, Potsdam, Germany, October, 1999.

Unpublished Presentations, Posters

Fencsik, D. E., Seymour, T. L., Mueller, S. T., Kieras, D. E., & Meyer, D. E. (2002). *Representation, retention, and recognition of information in visual working memory.* Poster presented at the meeting of the Psychonomic Society, Kansas City, MO, November, 2002.

Glass, J. M., Lauber, E. J., Schumacher, E. H., Kieras, D. E., & Meyer, D. E. (1997). *Aging and multiple-task performance: Task-coordination strategies in young and old adults.* Paper presented at the meeting of the Midwestern Psychological Association, Chicago, IL, May, 1997.

Glass, J. M., Schumacher, E. H., Meyer, D. E., Kieras, D. E., Zurbriggen, E. L., Gmeindl, L., & Lauber, E. J. (1998). *Cognitive aging and dual-task performance: Task-coordination strategies in young and old adults.* Paper presented at the Cognitive Aging Conference, Atlanta, GA, April, 1998.

Glass, J. M., Seymour, T. L., Schumacher, E. H., Gmeindl, L., Meyer, D. E., & Kieras, D. E. (1998). *Cognitive aging and task-coordination strategies for dual-task performance.* Poster presented at the meeting of the Psychonomic Society, Dallas, TX, November, 1998.

Kieras, D. (December, 2001). *Modeling human performance limitations in system design.* DARPA Augmented Cognition Conference, Austin.

Kieras, D. E., Meyer, D. E., Mueller, S., & Seymour, T. (1998). *An EPIC computational model of verbal working memory.* Poster presented at the meeting of the Psychonomic Society, Dallas, TX, November, 1998.

Lauber, E., Schumacher, E., Glass, J., Zurbriggen, E., Kieras, D. E., & Meyer, D. E. (1994). *Adaptive PRP effects: Evidence of flexible attention to action.* Paper presented at the meeting of the Psychonomic Society, St. Louis, MO, November, 1994.

Meyer, D. E. *Executive control and the interface with neuroscience.* (2000). Invited paper presented at the Conference on Executive Control, Errors, and The Brain. Jena, Germany, September, 2000.

Meyer, D. E., & Kieras, D. E. (1992). *The PRP effect: Central bottleneck, perceptual-motor limitations, or task strategies*? Paper presented at the meeting of the Psychonomic Society, St. Louis, MO, November, 1992.

Meyer, D. E., & Kieras, D. E. (1994). *Analysis of discrete and continuous information processing from the perspective of multiple-task performance.* Invited paper presented at the Conference on Discrete versus Continuous Processing of Information, Netherlands Royal Academy of Arts and Sciences, Amsterdam, The Netherlands, December, 1994.

Meyer, D. E., & Kieras, D. E. (1995). *Theoretical perspectives on cognitive aging from the viewpoint of the EPIC architecture for computational modeling of human performance.* Paper presented at the Southeastern Center Conference on Aging and Skill, Destin, FL, February, 1995.

Meyer, D. E., & Kieras, D. E. (1996). *EPIC: Adaptive executive control of human multiple-task performance.* Paper presented at the meeting of the Psychonomic Society, Chicago, IL, November, 1996.

Meyer, D. E., Kieras, D. E., Mueller, S., & Seymour, T. L. (1999). *Benefits of computational modeling for cognitive neuroscience studies of verbal working memory.* Poster presented at the meeting of the Cognitive Neuroscience Society, Washington, DC, April, 1999.

Meyer, D. E., Kieras, D. E., Schumacher, E. H., Fencsik, D., & Glass, J. M. B. (2001). *Prerequisites for virtually perfect time sharing in dual-task performance.* Paper presented at the meeting of the Psychonomic Society, Orlando, FL, November, 2001.

Meyer, D. E., Mueller, S. T., Seymour, T. L., & Kieras, D. E. (2000). *Brain loci of temporal coding and serial-order control in verbal working memory.* Poster presented at the meeting of the Cognitive Neuroscience Society, San Francisco, April, 2000.

Mueller, S. T., & Meyer, D. E. (2000). *Psychophysical chemistry of phonological similarity: A formal similarity metric based on principled phonetic feature analysis.* Paper presented at the meeting of the Society for Mathematical Psychology, Kingston, Ontario, Canada, August, 2000.

Mueller, S. T., & Meyer, D. E. (2001). *A neural network model of short-term verbal working memory based on transitory activation patterns.* Poster presented at the meeting of the Cognitive Neuroscience Society, New York, March, 2001.

Mueller, S. T., & Meyer, D. E. (2001). *Insights about verbal working memory and serial recall enabled by precise quantitative measurement of phonological dissimilarity.* Poster presented at the meeting of the Society for Mathematical Psychology, Providence, RI, July, 2001.

Mueller, S. T., Seymour, T. L., Glass, J. M., Kieras, D. E., & Meyer, D. E. (2000). *Components of cognitive aging in verbal working memory revealed by computational modeling with the Executive-Process Interactive Control (EPIC) architecture.* Poster presented at the biannual Cognitive Aging Conference, Atlanta, April, 2000.

Mueller, S. T., Seymour, T. L., Krawitz, A., Kieras, D. E., & Meyer, D. E. (2001). *Implications of articulatory duration and phonological similarity effects in working memory.* Poster presented at the meeting of the Psychonomic Society, Orlando, FL, November, 2001.

Schumacher, E. H., Glass, J., Lauber, E. J., Gmeindl, L., Woodside, B. J., Kieras, D. E., & Meyer,

D. E. (1996). *Concurrent response-selection processes in multiple-task performance.* Poster presented at the meeting of the Psychonomic Society, Chicago, IL, November, 1996.

Schumacher, E. H., Meyer, D. E., Kieras, D. E., Lauber, E. J., & Glass, J. M. (1997). *Concurrent response selection: Adaptive executive control of action.* Paper presented at the meeting of the Midwestern Psychological Association, Chicago, IL, May, 1997.

Schumacher, E. H., Seymour, T. S., Glass, J. M., Lauber, E. J., Kieras, D. E., & Meyer, D. E. (1997). *Virtually perfect time sharing in dual-task performance.* Paper presented at the meeting of the Psychonomic Society, Philadelphia, PA, November, 1997.

Schumacher, E. H., Seymour, T. S., Glass, J. M., Lauber, E. J., Kieras, D. E., & Meyer, D. E. (1998). *Virtually perfect time sharing in dual-task performance: Behavioral evidence for independent parallel processing in the human brain.* Poster presented at the meeting of the Cognitive Neuroscience Society, San Francisco, CA, April, 1998.

Wood, S. D., Kieras, D. E., & Meyer, D. E. (1994). *An EPIC model for a high-performance HCI task.* Poster presented at the HCI Consortium Workshop, Fraiser, CO, February, 1994.

Technical Reports

Kieras, D. E., & Meyer, D. E. (1994). *The EPIC architecture for modeling human information-processing and performance: A brief introduction.* EPIC Report No. 1 (TR-94/ONR-EPIC-1), University of Michigan, Ann Arbor, April, 1994.

Meyer, D. E., & Kieras, D. E. (1994). *EPIC computational models of psychological refractory-period effects in human multiple-task performance.* EPIC Report No. 2 (TR-94/ONR-EPIC-2), University of Michigan, Ann Arbor, June, 1994.

Meyer, D. E., Kieras, D. E., Lauber, E., Schumacher, E., Glass, J., Zurbriggen, E., Gmeindl, L., & Apfelblat, D. (1995). *Adaptive executive control: Flexible human multiple-task performance without pervasive immutable response-selection bottlenecks.* EPIC Report No. 3 (TR-95/ONR-EPIC-03), University of Michigan, Ann Arbor, June, 1995.

Kieras, D. E., Wood, S. D., & Meyer, D. E. (1995). *Predictive engineering models based on the EPIC architecture for a multimodal high-performance human-computer interaction task.* EPIC Report No. 4 (TR-95/ONR-EPIC-04), University of Michigan, Ann Arbor, October, 1995.

Kieras, D. E., & Meyer, D. E. (1995). *An overview of the EPIC architecture for cognition and performance with application to human-computer interaction.* EPIC Report No. 5 (TR-95/ONR-EPIC-05), University of Michigan, Ann Arbor, December, 1995.

Meyer, D. E., & Kieras, D. E. (1996). *A computational theory of executive cognitive processes and multiple-task performance: Part 1. Basic mechanisms.* EPIC Report No. 6 (TR-96/ONR-EPIC-06), University of Michigan, Ann Arbor, December, 1996.

Meyer, D. E., & Kieras, D. E (1997).. *A computational theory of executive cognitive processes and multiple-task performance: Part 2. Accounts of psychological refractory-period phenomena.* EPIC Report No. 7 (TR-97/ONR-EPIC-07), University of Michigan, Ann Arbor, January, 1997.

Meyer, D. E., & Kieras, D. E. (1997). Precis to a practical unified theory of cognition and action: Some lessons from EPIC computational models of human multiple-task performance. (EPIC Tech. Rep. No. 8, TR-97/ONR-EPIC-8). Ann Arbor, University of Michigan, Psychology Department. June 1, 1997.

Schumacher, E.H., Lauber, E.J., Glass, J.M.B, Zurbriggen, E.L., Gmeindl, L. Kieras, D.E., & Meyer, D.E. (1997). Concurrent response selection in dual-task performance: Evidence for adaptive executive control of task scheduling. (EPIC Tech. Rep. No. 9, TR-97/ONR-EPIC-9).

Ann Arbor, University of Michigan, Psychology Department. July 1, 1997.

Kieras, D. E., Meyer, D. E., Mueller, S., & Seymour, T.(1998). *Insights into working memory from the perspective of the EPIC architecture for modeling skilled perceptual-motor and cognitive human performance.* EPIC Report No. 10 (TR-98/ONR-EPIC-10), University of Michigan, Ann Arbor, January, 1998.

Kieras, D. E., & Meyer, D. E. (1998). *The role of cognitive task analysis in the application of predictive models of human performance.* EPIC Report No. 11 (TR-98/ONR-EPIC-11), University of Michigan, Ann Arbor, March, 1998.

Kieras, D. E., Meyer, D. E., Ballas, J. A., & Lauber, E. J. (1999). *Modern computational perspectives on executive mental control: Where to from here*? EPIC Report No. 12 (TR-99/ONR-EPIC-12), University of Michigan, Ann Arbor, August, 1999.

Kieras, D. E., Ballas, J. A., & Meyer, D. E. (2001). *Computational models for the effects of localized sound cueing in a complex dual task.* EPIC Report No. 13 (TR-01/ONR-EPIC-13), University of Michigan, Ann Arbor, January, 2001.

Doctoral Dissertations

Fencsik, D. *Representation and processing of objects and object features in visual working memory.* Doctoral Dissertation, Department of Psychology, University of Michigan, 2003.

Glass, J. M. B. *Aging and multiple-task performance: Task-coordination strategies in young and old adults.* Doctoral Dissertation, Department of Psychology, University of Michigan, 1996.

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