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Workload Modeling and Workload Management: Recent Theoretical Developments

by Raja Parasuraman and Ericka Rovira

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14. ABSTRACT

This report presents suggestions for potential enhancements of the workload modeling capabilities available within the U.S. Army Research Laboratory's Human Research and Engineering Directorate's Improved Performance Research Integration Tool (IMPRINT). These suggestions are based on a review of current theory and empirical evidence in the areas of workload modeling, prediction, and management. Nine suggestions for potential IMPRINT enhancements are identified, ranging from changes in the workload scales themselves to modifications of the logic with which management strategies are triggered. Relevant background sources, including theoretical bases, are provided and discussed.

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1. How to Read This Report

This report presents suggestions for potential enhancements of the Improved Performance Research Integration Tool (IMPRINT) modeling tool, based on a review of current theory and empirical evidence in the area of workload modeling and workload management. IMPRINT is a stochastic, discrete event, network modeling tool designed to assist in the evaluation of interactions of human users and system technologies through different phases of the system life cycle. Based on a review of theory and empirical studies, nine suggestions for potential IMPRINT enhancements were identified, as shown in the list in section 1.1. To see capsule summaries of these suggestions, read section 3. To see the relevant background theory behind each suggestion, see sections 4 and 5. Five of the suggestions pertain to workload modeling. The theoretical background material for these is given in section 4. The remaining four suggestions involve workload management strategies. The relevant background sources for these are given in section 5.

1.1 List of Suggestions for Potential Enhancements of IMPRINT

1. Revised or improved implementation of multiple resource theory: focal versus ambient vision
2. Cross-modal links in spatial attention
3. Time- and intensity-based models (Hendy's information processing [IP]/perceptual control theory [PCT] model)
4. MART: Malleable attentional resource theory
5. Dynamic workload modeling
6. Task prioritization
7. Cockpit task management (CTM)
8. Latent performance decrements
9. Task shifting

2. Overview and Scope

This document presents an outline of the theoretical foundations for enhancing the IMPRINT[1] computational workload modeling tool (Archer, 1998) with respect to two capabilities: workload modeling and workload management strategies. The goal of the project was to review and outline relevant theory and then to recommend enhancements for IMPRINT. Note that IMPRINT models were not run in this project. This would have allowed a more comprehensive evaluation of the implications of new workload theories or workload management strategies. However, this research was conducted in parallel with the work done by SIFT[2], Inc., in the evaluation of the current capabilities of IMPRINT. SIFT ran IMPRINT models to examine potential areas of difficulty and made suggestions for improvement (Miller, 2004). We closely followed the SIFT work and coordinated with them with respect to the suggestions that we made from a more theoretical orientation. Nevertheless, it is possible that some of the areas for enhancement that we suggest may be within the current capabilities of IMPRINT. Other suggestions may not be practically feasible within cost constraints.

For each of the two areas of workload modeling and workload management strategies, we offer potential areas of enhancement, based on the recent research literature. In all, nine suggestions for potential IMPRINT enhancements are identified. For each suggestion, we describe (1) the theoretical foundation, (2) the implications for IMPRINT, and (3) an initial "seat-of-the-pants" evaluation. We took an idealistic approach in which all possible enhancements could be considered, without consideration of cost, whether the change can be implemented, or other practical factors.

Our approach involved the following steps. We first conducted a selective review of the literature about mental workload modeling and workload management, focusing on material not covered in Mitchell's (2000) review. Next, we formulated initial recommendations for enhancements of IMPRINT, based on our analysis of the literature review. These recommendations were then discussed with U.S. Army Research Laboratory (ARL) personnel. We also communicated closely with SIFT, Inc., in the development of their "Core Desires for IMPRINT" report (Miller, 2004). We have commented on that document and also make some reference to that work. We have also noted where current theories and empirical data do or do not support some of the "core desires" identified by SIFT. However, in general, this report can be read independently of the SIFT work. In addition to the SIFT report, another document relevant to the present report is the SIFT document discussing the use of "red lines" or workload thresholds in IMPRINT (Miller, Parasuraman, Wu, & Neyens, 2004). The final list of recommendations reflected the joint input of ARL and SIFT.

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[1] http://www.arl.army.mil/ARL-Directorates/HRED/imb/imprint/Imprint7.htm

[2] Smart Information Flow Technologies

In section 3, we present these recommendations for enhancement of IMPRINT in the form of summary statements. We also provide supporting sections with relatively detailed reviews of current research on workload modeling and workload management (sections 4 and 5). These reviews can be considered the empirical foundation for the statements made in the summary section. The review of workload modeling is not comprehensive but is a revision of the previous review by Mitchell (2000), which was an ARL effort to provide an overview of mental workload theory as relevant to IMPRINT. We discuss the implications of new research for mental workload modeling since Mitchell's (2000) review.

Because the multiple resource theory (MRT) of Wickens (1984) was highly influential in the development of several computational models of workload, including those embedded within IMPRINT, we also discuss a recent review of the current status of that theory by Wickens (2002), especially because that paper also discusses implication for computational models of workload. That review was limited to MRT, so we also examined other recent sources of evidence relevant to mental workload theory. Finally, the Mitchell (2000) review of workload assessment was relatively comprehensive, but its coverage of workload management strategies was somewhat cursory, whereas we provide a relatively detailed review of current research on workload transition, task scheduling, and task shifting. We draw implications from this work for potential enhancement of workload management capabilities within IMPRINT.

3. Potential Enhancements of Workload Modeling and Workload Management Strategies

We conducted a review of the literature on mental workload theory relevant to IMPRINT, focusing on studies published since the previous review by Mitchell (2000) or studies that were not discussed in the Mitchell review. Based on this review, the following nine recommendations represent areas in which IMPRINT might be enhanced. The suggestions are provided as capsule summaries only. For details about the theories and empirical evidence behind each recommendation, see sections 4 and 5.

3.1 Revised Multiple Resource Theory: Focal Versus Ambient Vision

Theoretical Foundation: There is evidence that the visual modality module in MRT needs to be subdivided into focal and ambient sub-modules (Wickens, 2002).

Implications for IMPRINT: Provide guidance and support for users wishing to define resource channels, including the focal/ambient distinction and the resulting conflict matrix.

Initial Evaluation: Implement, given strong background evidence.

3.2 Cross-Modal Links in Attention

Theoretical Foundation: Although different sensory modalities generally define different resource pools, cross-modal links are present, particularly as a function of common spatial location (Spence & Read, 2003).

Implications for IMPRINT: Revision of workload model, particularly the sensory modality resource type, and the resulting conflict matrix.

Initial Evaluation: Implement, given strong background evidence for importance of cross-modal links in spatial attention.

3.3 Time and Intensity Based Models (Hendy's IP/PCT Model)

Theoretical Foundation: Time to perform a task as a function of time available can be used to predict overall workload, whereas intensity of processing has a lesser effect (Hendy, Liao, & Milgram, 1997).

Implications for IMPRINT: Revision of workload model, eliminating resource demand and conflict matrix and replacing with a percentage time metric.

Initial Evaluation: Do not implement, given that percentage time metrics cannot account for lack of interference from time-consuming but minimally resource-demanding tasks. Using resource demands and the conflict matrix gives a designer better, more concrete, recommendations pertinent to workstation redesign, which are therefore more valuable than time-based methods.

3.4 MART

Theoretical Foundation: The view that attentional resources, while clearly limited, are fixed, is an assumption that has often not been tested. Some recent studies suggest that the limit may "expand," particularly in conditions when there is a shift from task underload to overload conditions (Young & Stanton, 2002).

Implications for IMPRINT: Revision of workload model, including the ability to change resource demand and conflict values as a function of total task load. Not clear how this could be easily implemented.

Initial Evaluation: Should be considered, but currently there is not a large body of empirical evidence to support this theory.

3.5 Dynamic Workload Modeling

Theoretical Foundation: Most theories of workload are relatively static and do not explicitly model dynamic variations related to how far the operator thinks he or she is from achieving the mission goal. In contrast, work by Hancock and colleagues (Hancock & Caird, 1993; Hancock

& Warm, 1989) suggests a dynamic model in which workload is a vector with three dimensions: (1) time for action, (2) perceived distance from the desired goal, and (3) level of effort required to achieve the desired goal. Mental workload increases as the distance to the goal and time constraints increase.

Implications for IMPRINT: Revision of workload model, including metrics of these three dimensions. Not clear how this could be easily implemented.

Initial Evaluation: This theory has some promise but is currently underdeveloped and not fully validated; therefore, it is not ready for implementation.

3.6 Task Prioritization

Theoretical Foundation: There is a large body of evidence to support the view that task prioritization is a major strategy used by operators to handle increases in task demands.

Implications for IMPRINT: Task prioritization based on an overall workload threshold is a current feature of IMPRINT. However, other prioritization methods (e.g., one based on variable thresholds, dependent on task resource values) are also possible and could be implemented in IMPRINT.

Initial Evaluation: MRT and other resource theories provide general support for task prioritization, based on differential resource values. However, we are not aware of any specific study that has attempted to validate such a strategy.

3.7 Cockpit Task Management (CTM)

Theoretical Foundation: Work by Funk (1991) has shown that in addition to task prioritization, pilots use a number of other fairly well-specified strategies to handle overload.

Implications for IMPRINT: Provide support to the IMPRINT user to implement strategies other than task prioritization in CTM (e.g., resource allocation).

Initial Evaluation: The CTM approach has been validated in pilots and flight simulation, but its extrapolation to other domains is unclear.

3.8 Latent Performance Decrements

Theoretical Foundation: Although this is not directly a workload management strategy, this concept, developed by Hockey (1997), represents the *outcome* of one strategy, the “active control mode”. Hockey has shown that during overload conditions, operators attempt to “protect” what they consider the primary task by expending more effort and assuming an “active control” mode. This can lead to latent performance decrements in which lower priority tasks can suffer disruptions.

Implications for IMPRINT: The active control mode could be modeled in IMPRINT with user-chosen values for two variables (the increased workload associated with the primary task and the maximum time the strategy can be active) before performance breakdown.

Initial Evaluation: There is fairly good empirical support for Hockey's theory and thus it may be worthwhile considering implementation of the active control mode strategy in IMPRINT.

3.9 Task Shifting

Theoretical Foundation: There is a large body of empirical evidence and supporting theory showing that operator performance shows significant costs in speed or responding and accuracy when operators shift between two or more tasks.

Implications for IMPRINT: Currently, IMPRINT permits an interrupted task to be assigned a time penalty when it is restarted. However, there is no easy way to specify a cost in workload that would impact performance of other tasks.

Initial Evaluation: This is an area for enhancement of IMPRINT, given the strong empirical and theoretical support for task shifting costs.

4. Mental Workload Modeling: Theoretical Foundations

4.1 The Need for Analytical Models

Mental workload can be viewed as an intervening construct that reflects the relationship between the demands of an environment placed on the operator and the capability of the operator to meet those demands (Parasuraman & Hancock, 2001; Wickens, 2002). Because operator mental workload can be the restrictive element in any attempt to increase system efficiency and capacity, workload must be assessed in the design of a new system. Two classes of mental workload assessment techniques are empirical and analytical methods. Empirical techniques attempt to determine a specific level of workload by a physically measurable quantity, usually by the evaluation of performance of primary and secondary tasks, measuring operator physiological state, or using subjective measures. Analytical models and simulations, on the other hand, are procedures for predicting workload without operator measurement (Aldrich, Szabo, & Bierbaum, 1989; Archer, 1998; Dahl, Laughery, & Hahler, 1991). However, in principle, such analytical methods are based on workload theories that have been validated in empirical studies.

The Department of Defense has sought to strengthen the application of modeling and simulation to promote their effective use in training, military operations, and development of systems (Kameny, 1995). In an effort to meet the goals of acceptable performance levels and the reduction of costs, the military has focused on expanding the use of models and simulations in designing systems that require substantial mental work by the user. Given the constraints of time and expense, the modeling and simulation approach, specifically analytical modeling tools, provides a very good opportunity for comparing all possible candidate system configurations (See & Vidulich, 1997).

The modeling approach is advantageous because system and operator performance can be evaluated before the construction of a system or the alteration of a current system. This saves both the time and expense involved in the construction of a new system which may not be an improvement over the existing system. Alternatively, the new system may not provide the effects intended or may exhibit unexpected behavior with catastrophic consequences. Having recognized the utility of models, researchers and designers are using them widely in a range of domains. Models of mental workload, however, do have some limitations that need to be understood so that they can be successful predictors of workload. Analytical models can be difficult to validate, are sometimes too general, and may not be sufficiently sensitive to individual and team differences in performance. Such models are also bound by current theoretical and empirical knowledge of human information processing. This literature review in part is associated with the third problem in that new research regarding mental workload theory, task shifting, and task scheduling has arisen and thus should be considered for incorporation into the IMPRINT simulation tool.

In his recent revised review of MRT, Wickens (2002) provides some suggestions for improved computational modeling of workload. He proposes that any such model should have the following three features:

1. Represent each task as a vector of its resource demands, including what resources and how many resources.
2. Identify the amount of load on each resource.
3. Compute performance loss by the sharing of resources or by the total demand from both tasks being particularly high.

In order for this to be accomplished computationally, Wickens (2002) suggests that the model needs five components:

a. A task analysis shell in which task demand levels from different resources can be entered.
b. A conflict matrix that determines the amount of conflict between resource pairs.
c. A computational formula that calculates the penalty on performance for task pairs including total resource demand and conflict between tasks and resource pairs.
d. A task interference value that is given to one task or the other, taking into account resource demand as well as conflict.
e. A time line analysis included for tasks that are time critical.

IMPRINT and other computational models currently have some of these features. However, what remain to be determined are specific instantiations of these features and whether additional features should be added, depending on advances in mental workload theory. We turn now to that issue.

4.2 Recent Perspectives on Mental Workload Theory

4.2.1 Focal Versus Ambient Vision

Theories of mental workload initially assumed that the attentional resources supporting task performance were undifferentiated or unitary (Moray, 1967; Kahneman, 1973). Subsequently, researchers postulated the existence of multiple resource pools, which led to the development of the multiple resource theory of workload (Wickens, 1984). The multiple resource view, most commonly associated with Wickens (1984), but also proposed in a different form by Baddeley (1986), suggests that multiple, independent, limited capacity pools of resources can be allocated to different processing activities. The Wickens (1984) model has recently been revised from its initial three modules for processing stages, sensory modalities, and processing codes. The three main modules remain, but the visual processing pool within the sensory modality module is now sub-divided to differentiate between focal and ambient visual processing (Wickens, 2002). Focal vision refers to tasks that require the stimulus to be brought into the high-resolution area of the retina and the fovea, as in form and object discrimination tasks. Other visual tasks, however, such as navigating through a space or avoiding large objects, can be performed by stimulation outside the fovea (parafovea), a form of vision that is termed “ambient vision”.

Research has shown that the modules described in MRT by Wickens (2002) are distinct in a number of ways. For example, within the processing stage module, perceptual and cognitive processing stages share the same resource pool, whereas response selection and execution stages use resources from a separate pool (Isreal, Wickens, Chesney, & Donchin, 1980; Shallice, McLeod, & Lewis, 1985; Wickens, 2002). Whether sensory modality defines different resources is presently unclear, and as discussed in the section on cross-modal attention, there may be some evidence against this view. Nevertheless, sensory modality does define different structures or channels for information presentation. Within-channel interference may be greater than between-channel interference when tasks are combined. For example, various researchers have shown that cross-modal stimulation (e.g., one auditory and one visual channel) better supports time-sharing performance versus intra-modal time sharing (e.g., two auditory messages) (see Wickens, 1984, for a review).

Wickens (2002) now proposes that the visual modality itself be subdivided on the basis of whether visual processing requires focal or ambient vision. There is increasing evidence that focal and ambient vision differ, so that they can be time shared more efficiently than either type of visual processing with itself. For example, discriminating the fine detail of a visual target cannot be efficiently time shared with similar processing for another target, since both require focal vision, whereas it may be time shared with navigating through an environment, which can be supported by ambient vision. Focal and ambient vision may also recruit different brain networks (Weinstein & Wickens, 1992; Previc, 1998). Focal vision is foveal and thus is important for attention to detail, reading text, pattern recognition, etc. Ambient vision is necessary for peripheral vision, sensing orientation, and ego motion. It remains unclear whether ambient vision uses different resources or is processed automatically by the brain, thus needing limited attentional resources. Nevertheless, because focal and ambient visual processing can be time shared, designers are attempting to find ways to take advantage of using ambient vision in situations when focal vision is heavily taxed.

4.2.2 Cross-Modal Links in Spatial Attention

Attempting to reduce interference by distributing information sources between focal and ambient vision represents an example of *within*-modality manipulation. It is well known that *across*-modality division can also reduce dual-task interference (Treisman & Davies, 1973). Because of evidence that, for example, a visual and an auditory task could be time shared more efficiently than two visual or two auditory tasks, Wickens (1984) includes sensory modality as defining a distinct module in the original MRT model.

Despite the view that cross-modality pairings can reduce interference because of the tapping of different resources, there is also evidence that there are significant cross-modal links in attentional processing (Driver & Spence, 1998). These links appear to extend to all sense modalities. For example, one recent study found extensive cross-modal linking for *all possible* pairings of vision, audition, and touch (Spence, Lloyd, McGlone, Nicholls, & Driver, 2000). At one level, this evidence might be seen as supporting a unitary resource model as opposed to MRT, but the implications of this work actually go beyond such a simple characterization. Rather, the evidence of cross-modal links suggests that resource conflict might not be simply determined by sensory modality but by other factors as well.

One such factor is spatial location. Spence and Read (2003) showed that dual-task performance can be influenced by the nature of cross-modal links in spatial attention. They showed that combining simulated driving with speech shadowing was more difficult when the speech originated from the side (as from a passenger) than from the front, which was the primary source of input for the driving task. The frontal speech advantage was more pronounced when participants performed the demanding simulated driving task at the same time as shadowing than when they performed the shadowing task alone. Thus, people process auditory information more efficiently and show lower dual-task decrement when auditory and visual stimuli are presented from the same, rather than different, spatial locations. These results have clear implications for the design of better user interfaces and for workload models.

In other instances, however, as outlined by Wickens (2002), it remains unresolved if the reason for cross-modal improvement in performance is attributable to separate auditory and visual resources in the brain or to factors including visual peripheral issues. For instance, if two visual displays are far apart, there will be an added cost because of visual scanning; in a similar manner, if two auditory messages are too close in time, there will be a cost of interference. Also, cross-modal time-sharing performance improvements may be attributable to auditory information qualities including attention capture and pre-emption.

4.2.3 Time and Intensity Modeling of Workload (Hendy's IP/PCT model*)*

This model, proposed by Hendy, Liao, and Milgram (1997), is an extension of previous time line models of mental workload. The model combines a simple IP model with a PCT model. The IP model may be used in conjunction with PCT (Powers, 1973), which refers to human-machine and human-human interactions, whereas the IP model describes the information processing components within each. IP/PCT makes explicit a system's goal and the shaping of perceptions and behavior by an internal knowledge state and it makes feedback necessary for goal achievement (Hendy, East, & Farrell, 2001). Time line models can be thought of as single-channel models that assume that attention is indivisible and must be allocated to a given task in an all-or-none fashion. Consequently, workload (and overload) in these models arises when there is a proportional lack of time to execute a task in relation to the time available. Not surprisingly, therefore, these models emphasize time pressure as the major contributor to workload.

The IP model is based on two main elements: time load and intensity load. Time load pertains to the time pressure involved in completing the task and is defined as the ratio of decision time to the total time available. Intensity refers to task difficulty (i.e., bits of information to be processed) and the capacity of the operator to meet those demands (i.e., the processing rate). The model suggests that the human information processor may reduce the mismatch in information processing load and the ability of the operator to meet those demands by (a) increasing the capacity of the channel to process information, (b) reducing the task load or the quantity of information that needs to be processed, or (c) increasing the available time to make a decision (Hendy et al., 1997). Channel capacity may change because of physiological and psychological states, including fatigue and anxiety. It has been argued that the effect of stress is the reduction of available attention capacity (Hancock & Warm, 1989; Hancock, Wulf, Thom, & Fassnacht, 1990). An operator may reduce the quantity of information processed by changing strategy or the depth of processing. This can be seen when an operator shifts from knowledge-based to rule-based to skill-based activity (Rasmussen, 1986). Operators rely on strategies that help them keep workload within their capacity limits. For instance, Sperandio (1978) showed that during high traffic load, air traffic controllers reduced the number of variables that they attended to by grouping aircraft. Hendy et al. (1997) also cite an example when operators deliberately increased the time available to solve a problem, indicating that they were willing to allow error to accumulate before they took final corrective measures.

The IP/PCT model predicts operator performance as the ratio of the amount of information processed to information demanded to be processed. Operator error is related to the amount of information unprocessed. Therefore, as the amount of information demanded to be processed increases and the capacity to process becomes insufficient, the performance ratio will decrease as the number of errors increase. This theory poses a challenge to resource theory in that it posits that a major missing component of resource theory is its ability to encompass the factor of time explicitly (Hendy et al., 1997).

Hendy et al. (2001) found supporting evidence for the IP/PCT model using a simulated air traffic control environment. They used two variables, N, the number of aircraft in the scenario (bits of information to be processed) and T, the time in which all decisions needed to be made. They found that time pressure was a factor in determining the performance of the human information operator in the environment.

This model is potentially useful because it attempts to unite attention theory with the earlier research of operator performance measurement that has been based on time analysis. However, a major limitation of the model as it stands is that percentage time metrics cannot account for lack of interference from time-consuming but minimally resource-demanding tasks, as can MRT or other resource theories.

4.2.4 MART

Young and Stanton (2002) recently proposed a new theory of mental workload in an attempt to explain the frequently observed phenomenon of performance decrements following periods of underload (or seemingly low task load such as that stemming from periods when automated functions are used). Wickens and Hollands (2000) and de Waard (1996) have noted that performance frequently follows an inverted U-shaped curve similar to the performance-arousal curve. That is, when task demands are low, performance may be poor and then performance may actually improve with increasing task difficulty until a certain point at which further increases in task demands result in deteriorating performance. According to Young and Stanton's MART, attentional resource pools are not of fixed capacity but shrink when task load is low and increase with increasing task demands. Automation can result in mental underload, which in turn results in a decreased attentional resource pool capacity that leaves the operator susceptible to an inability to perform when automation fails. MART results in predictions similar to those found during the commonly observed vigilance decrement (Parasuraman, 1979). In fact, the phenomena may be difficult to distinguish. To date, MART has only been validated by studies conducted by the same authors. We are not aware of any independent validation. However, even with this caveat, MART may be a potential candidate to consider for enhancement of IMPRINT. Implementation would require modification of the resource values in the underlying workload model in relation to the total workload imposed on the operator.

4.2.5 Dynamic Workload Modeling

The Wickens and Baddeley models of workload do not explicitly model the dynamic aspects of workload, in which operators use strategies to keep their workload within a manageable range. Such workload management strategies are discussed later in this document, but for now, notice that many researchers see the need for expanding workload theory to include such dynamic factors. Parasuraman and Hancock (2001) described workload as a "dynamic and multiply determined" function of the combination of task demands, operator strategies, and the work environment. As task load increases, operators may adopt adaptive control strategies to offset performance consequences and to maintain workload within a manageable range. Operators may change their performance criteria, offset tasks to other personnel, or engage automation systems in order to allocate attention to critical task components. Many of these operator strategies are discussed further in a later section. Hancock and Caird (1993) conceptualized workload as having three dimensions: (1) time for action, (2) perceived distance from the desired goal, and (3) level of effort required to achieve the desired goal. According to this perspective, mental workload increases as the distance to the goal and time constraints increase. This perspective illustrates the importance of considering task and operator variables, two influences that are discussed further in the next section.

5. Workload Management Strategies

5.1 Current IMPRINT Workload Management Modeling

IMPRINT currently has six workload management strategies. One of the six strategies may be implemented when an operator's workload level exceeds the workload threshold:

A - No effect, all tasks are performed, regardless of overload (default or "null" strategy.

B – Does not begin the new task. New task is not started by another operator.

C – Tasks are performed sequentially, beginning with the ongoing task and then the new task.

D – Ongoing task is interrupted, new task is started. Ongoing task is started in "windows of opportunity". (The operator attempts to take advantage of subsequent lower workload levels to resume the task.)

E – New task is reallocated to the contingency operator.

F – Ongoing task is reallocated to the contingency operator.

Along with the available strategies the workload management window displays a list of variables the analyst can use to build logical expressions. The variables are

P - The priority of the new task,

H - The highest priority of the ongoing task,

T - The total workload level for the operator (after the new task is added), and

S - The operator's workload threshold.

In the following sections, we consider a broad range of research on workload management. We examine whether the myriad factors that influence human operator workload management strategies might have implications for enhancing IMPRINT. We also examine the effects of these and related factors on operator performance, so that the implications for workload can also be better understood.

5.2 Workload Transition: From Underload to Overload and Back

Numerous investigations have examined the mental workload involved in situations requiring long periods of vigilant task performance and underload (Hancock & Caird, 1993; See, Howe, Warm, & Dember, 1995; Young & Stanton, 2002), as well as in high workload multi-task situations (Hancock et al., 1990; Verwey & Veltman, 1996). However, the workload associated with transitioning between various task states (i.e., from prolonged underload to sudden time-critical high workload conditions) has received considerably less attention (Warm, 1993).

In many real-world tasks, critical task performance requires the ability to maintain vigilant attention for extended periods of time while maintaining readiness to perform demanding time-critical tasks at short notice. The ability to achieve high levels of skilled performance following the sudden transition between workload task states is an essential requirement of positions such as lifeguards, tank crew operators, trans-oceanic pilots, long distance truck drivers, and nuclear power plant operators when faced with abnormal, potential crisis situations. Such situations are typically characterized by periods of prolonged underload followed by the sudden onset of multiple task demands, often in the presence of multiple stressors.

The performance consequences of workload transition are complex (Huey & Wickens, 1993). The direction of workload transition (low to high versus high to low) as well as task, environmental, and operator variables affect performance. Task variables include the complexity of the demands (Warm, 1993) and the working memory requirements imposed. Additional task variables include task structure (modalities and organization of task combinations), presentation rates, performance criterion, task duration, variability and fluctuation schedules of task demands. Operator variables include the operator's state (fatigued or sleep deprived) and control mode (Hockey, 1997; Sauer, Wastell, & Hockey, 1997) as well as strategies, expectations, and beliefs about the tasks (Matthews, 2001). Human operators are capable of maintaining performance across workload transitions through a variety of adaptive procedures, including changing strategies and performance criteria (Hockey, 1986; Hockey, 1997; Parasuraman & Hancock, 2001). However, adaptations to workload transitions are not without cost.

Workload transitions frequently result in decrements in skilled performance. In particular, workload transitions are associated with impaired decision making, reduced communication efficiency (Hockey, Wastell, & Sauer, 1998; Sauer et al., 1997), decrements in performance of peripheral tasks, and a shift to less effort-demanding processes (such as strategies with lower working memory requirements) (Hockey, 1997). Each of these issues is examined in further detail.

Whereas underload is associated with reduced alertness, decreased perceptual sensitivity (See et al., 1995), and lowered attention, overload is associated with distractions, diverted attention, and insufficient time for adequate information processing (Brookhuis & de Waard, 2001). The performance consequences of transitions between these two states appear to depend on a complex interaction between the direction of the transition (high to low versus low to high), the task structure, and operator variables and strategies. Prior workload states may affect future workload states by reducing resource capacity or by requiring the operator to change strategies. For example, Young and Stanton (2002) have proposed that resources may adapt to fit the demands of the task at hand. Therefore, during periods of underload, resource capacity may be reduced, leaving an operator less able to respond to sudden increases in task demand. The implications of this MART model were considered in the workload modeling section of this document. Others (Hockey, 1986; Hockey, 1997; Parasuraman & Hancock, 2001; Sperandio, 1978), have proposed that operators change their strategies, control methods, and performance criteria in an effort to cope with workload transitions. These operator control strategies, in and of themselves, may have important performance consequences in post-transition periods.

Hockey (1997) and Matthews (2001) distinguished between several discrete operator control modes that may have important performance implications following workload transition. A "strain" mode exists when the system or operator must maintain performance in demanding situations by exerting so much effort that discomfort and physiological costs are accrued. Conversely, a passive or fatigue mode exists when the system or operator lowers performance expectations, thereby reducing demands.

To a large extent, humans are capable of regulating effort to match desired performance levels. Self-regulation involves altering the direction, amount, and form of expended effort in order to achieve desired performance levels (Matthews, 2001). Perceptions of the situation as well as operator control mode can affect self-regulation of effort. For example, an environmental stimulus such as noise can improve performance in a fatigued operator while decreasing performance in a strained operator, particularly if the operator perceives the noise as a negative stressor.

This model suggests that although humans possess a limited number of resources, they are able to make strategic resource management decisions to allocate and control energetic resources. Within this framework, operators could be expected to adapt to workload transitions by strategically controlling their resource allocation. However, increasing the mental resources afforded to a given task is not without consequences. Since additional mental resources must be devoted to task performance, a toll is placed on emotional and physiological sub-systems. This toll is particularly taxing when it occurs during conditions of *chronic perturbation from stress and environmental load*—conditions that could be expected to be present after sudden workload transition. Operators experience the demand for increased mental effort as straining subjectively and physiologically (Hockey, 1997). Disruption of auxiliary tasks and latent performance decrements can occur with prolonged task demand even when primary task performance remains stable. Additionally, one method of compensation is for the operator to adapt his or her performance strategy or control mode.

Hockey (1997) discusses the relativity of performance goals, reminding us that operators do not always prioritize task goals the same way that investigators or other outside agents may. Maintaining sustained effort is challenging and may compete with other personal and biological goals. Operators may adopt one of three strategies in order to compensate with stressful demanding task situations. Hockey refers to each strategy style as a mode of control and distinguishes between (a) active coping mode, (b) strain coping mode, and (c) passive coping mode. Active control refers to a strategy of increased working memory or executive control (Baddeley & Hitch, 1994) or the use of Rasmussen's (1986) rule- or knowledge-based level of responding. Strain coping refers to states where the operator exerts maximum effort during conditions when task demands are perceived to exceed mental resources. Strain coping modes are associated with anxiety, fatigue, and high levels of sympathetic dominance and increased excretion of catecholamines and cortisol. The physiological effects of strain coping modes become problematic after extended periods of time but show few detrimental consequences for short-term periodic exposures. The third and final control mode is the passive coping mode, which refers to a state when the operators allow performance to degrade, reducing expected levels of speed or accuracy or in extreme cases, completely disengaging from task goals. Passive control mode is associated with increased adrenocortical activity similar to levels in environments with restricted control or states of helplessness. While active coping responses may appear on the surface to be preferred operator states, particularly for emergency response situations, Hockey points out that prolonged periods of using the active control state may be maladaptive and may lead to latent performance decrements.

Latent performance decrements (Hockey, 1997) may occur when the cost of achieving task goals causes disruptions of lower priority goals and processes. In these circumstances, the operator may be able to maintain primary task performance but not without incurring latent costs. Latent performance decrements can result in reduced system efficiency, as manifested in an inability to compensate for additional, sustained, or changing task demands. Latent performance decrements may manifest in four types of performance breakdown as identified in table 1 (from Hockey, 1997, p. 84).

Table 1. Types of latent decrement associated with performance protection under stress and high demand (taken from Hockey, 1997).

Type of Latent Decrement	Characteristics (with examples)
Subsidiary task failure	Selective impairment of (currently) low priority task components Neglect of subsidiary activities Attentional narrowing
Strategic adjustment	Within-task shift to simpler strategies Less use of working memory Greater use of closed loop control Shift from knowledge-based to rule-based behaviors
Compensatory costs	Strain of active control during performance maintenance Increased mental effort Sympathetic dominance
Fatigue after-effects	Post-task preference for low effort strategies Subjective fatigue Risky decision making

As workload increases, tasks or aspects of tasks deemed less important (at the time) may be performed less accurately or efficiently in an effort to maintain acceptable levels of primary task performance. This relationship forms the foundation of an extensive body of empirical work using the dual task method of assessing mental workload (O'Donnell & Eggemeier, 1986; Ogden, Levine, & Eisner, 1979). Sudden transition from underload to high workload states can be expected to have effects similar to those in general stress conditions, particularly if the operator is fatigued. Stress results in a narrowing of attention. Thus, for instance, a fatigued driver faced with the sudden onset of adverse weather conditions might be able to maintain control of the vehicle but performance of auxiliary tasks will degrade (i.e., monitoring of engine lights, conversations with passengers, using turn signals appropriately).

Operators may maintain performance of primary tasks by making strategic adjustments in the allocation of processing resources. They may emphasize accuracy while sacrificing speed or vice versa. Operators may also choose strategies that decrease working memory requirements (Hockey, 1997) or may shift toward less resource-intensive modes of operating (e.g., shifting from knowledge-based to rule-based modes of operation in Rasmussen's 1986 taxonomy). Such strategies may maintain primary task performance while being less operationally efficient.

Hockey (1997) points out that operators may also maintain primary task performance during overload conditions by exerting additional effort. The compensatory costs of this exertion may manifest in physiological consequences such as sympathetic, musculo-skeletal responses and neuroendocrine stress patterns. For short durations, these compensatory costs may not result in significant problems. However, if the state of physiological exertion must be sustained for long periods of time, fatigue after-effects are probable.

Returning to conditions of lower demand after prolonged periods of high demand can be expected to be affected by fatigue after-effects (Hockey, 1997). Fatigue after-effects will manifest in operators choosing strategies that require less effort even if they are more risky.

Operators will tend to reduce the amount of controlled effort expended toward a task following prolonged exertion.

In sum, operation methods during a post-transition period involve changes in strategies, and since cognitive demands tend to be high, the adopted strategies will often be methods that place fewer demands on reasoning and cognitive resources. Tasks are prioritized, although again, the operator's ability to effectively prioritize tasks may be compromised because of heavy processing demands. Finally, there tends to be an increased need for communication during the post-transition period, but high workload and lack of shared context may result in less effective communications. Specific task variables may mediate or exacerbate performance after workload transition.

5.3 Task Scheduling and Prioritization

Following transition from low to high workload, operators may change to less cognitively demanding strategies. As discussed previously, Sperandio (1978) examined workload transition among air traffic controllers as the number of aircraft in the controllers' sector fluctuated. He observed that during high workload periods, controllers changed to operating procedures that required less effort and they tended to relax their self-imposed performance criteria. A shift to more "economical" strategies is characterized by a narrowing of task focus to subsets of information deemed critical at the current moment. As workload demands increase, operators may switch to a sequential rather than concurrent task performance strategy. Tasks are prioritized, communications change quantitatively and qualitatively, and situation assessment and contingency planning is conducted for shorter temporal durations.

Cognitive activities increase in transitions from low to high workload situations, particularly when the increase is attributable to unexpected events. Operators may need to rely extensively on prior knowledge to understand system functions and to determine system components likely to be affected. Plans must be revised and integrated with changing system states and task priorities (Woods & Patterson, 2001). New strategies must be adopted to offset extreme workload states and to preserve system operations (Parasuraman & Hancock, 2001).

During periods of relatively low workload, operators may engage in a full range of operational tasks, including engaging in careful primary task execution, planning for system efficiency (i.e., optimal navigational routes, fuel consumption), and planning for potential unexpected future events or circumstances (i.e., alternate routes if traffic density increases or delays are encountered). However, as workload begins to increase, these reasoning activities may be compromised. Operators must prioritize tasks and postpone or delegate auxiliary tasks. Offsetting workload to automated agents is a positive aspect of adaptive control. However, the task of engaging automation may require, at least initially, an increase in the number of control activities as information is programmed into the automation management systems (Parasuraman, Sheridan, & Wickens, 2000).

High workload is associated with significant decrements in operators' ability to effectively prioritize tasks. For example, significant degradations in pilots' ability to prioritize tasks have been observed as a function of flight path complexity and increases in the number of tasks to be performed (Funk & Braune, 1999). A particularly dramatic example of pilot failure to effectively prioritize tasks was the 1972 crash of Eastern Airlines flight 401 in the Florida Everglades. During an approach at the Miami Airport, the entire flight crew became preoccupied with diagnosing a malfunction in one of the landing gear lights. The captain accidentally disengaged the autopilot and none of the preoccupied crew members noticed the slow steady descent of the aircraft to the ground, killing 100 of 176 people on board (National Transportation Safety Board, 1973).

Task scheduling, which is a particular form of task management, pertains to having to schedule a plan for the performance of various tasks and subtasks. Operators, in demanding workload environments, need to perform task management because they do not possess the necessary resources to simultaneously execute all the tasks that demand their attention (Wilson & Funk, 1998). It is important for operators performing a complex goal to prioritize all tasks and sub-tasks and then allocate their resources accordingly. For instance, higher priority tasks should typically be allocated resources before lower priority tasks. If operators give their attention to a lower priority task to the detriment of a higher priority task, a task prioritization error is committed (Wilson & Funk, 1998). However, there may be cases when simple prioritization and assigning resources (as in IMPRINT) may be insufficient. The time deadline to complete all tasks must also be taken into account. In certain circumstances, it may be acceptable to expend extra effort on a lower priority task to "get it out of the way" and still leave sufficient time and resources to complete the more important task.

Generally, beginning commercial pilots are taught to prioritize tasks according to the following strategy: aviate, navigate, communicate, and manage. Aviate means pilots are responsible for using the flight systems to fly the aircraft. Navigate concerns planning the route as well as making any route changes. Flight communications pertain to communication with ground crew, flight crew, cabin crew, and passengers. Finally, pilots are taught to manage and to plan when these tasks are to be performed and in with what priority.

Task scheduling can be accomplished with successful task prioritization. Funk (1991) provides an outline for concurrent task management (CTM). The multiple concurrent task demands of high workload situations require the operator to initiate task management strategies. Funk and colleagues (Chou, Madhavan, & Funk, 1996; Funk & Braune, 1999) discuss components of CTM that have implications for a wide variety of high workload environments. Funk (1991) described seven discreet behaviors associated with task management. See table 2 for a list of identified task management-related activities.

Table 2. Task management activities (adapted from Funk 1991; as described in Funk et al., 1996, pp 308-309).

Activity Component	Description
Task Initiation	The initiation of tasks when appropriate conditions exist.
Task Monitoring	The assessment of task progress and status.
Task Prioritization	The assignment of priorities to tasks relative to their importance and urgency for the safe operation of the mission.
Resource Allocation	The assignment of human and machine resources to tasks so that they may be completed.
Task Interruption	The temporary suspension of lower priority tasks so that resources may be allocated to higher priority tasks.
Task Resumption	The resumption of interrupted tasks when priorities change or resources become available.
Task Termination	The termination of tasks that have been completed, that cannot be completed, or that are no longer relevant.

Task management errors occur when operators perform any of these task management-related activities at an inappropriate time (early or late), fail to perform a particular task appropriately, or perform the activity incorrectly (Chou et al., 1996). Task management errors are involved in a substantial number of aviation accidents and incidents. For example, in a recent large scale review, Chou et al. (1996) found evidence indicating that CTM errors played a critical role in more than 20% of the aviation accidents and nearly 50% of the aviation incidents studied. They found that in a high workload flight situation (high levels of visual, manual, and mental resource requirements), tasks took longer to initiate and complete and task prioritization performance degraded significantly. Task prioritization appears to play a critical role in the maintenance of performance in high workload situations.

Despite the wealth of information regarding various workload states, as Hancock and colleagues (1995) point out, most of this research has been generated by the manipulation of the absolute level of task demand. Thus, the influence of previous task demands and the task context has received relatively little attention. Previous task demands have the potential to influence performance, regardless of the absolute demands of the current task.

In a recent study, Bishara and Funk (2002) trained operators to prioritize tasks. Their goal was to devise a strategy to assist operators in task prioritization via training. As previously mentioned, pilots already have a general priority scheme: aviate, navigate, communicate, and manage systems. Researchers sought to teach operators a task management procedure called APE (assess, prioritize, and execute). Three groups of instrument flight rule (IFR) rated pilots completed a pre- and post-training flight. Group 1 received no training; they took a break between the pre- and post-training flights. Group 2 received descriptive training which included an introduction to CTM, two National Transportation Safety Board accident reports, six aviation safety reporting system (ASRS) aircraft incident reports, an explanation of how CTM contributed to those incidents and accidents, and a summary of factors that pilots should be aware of to avoid CTM errors. Group 3, the prescription group, received all of the above plus training in a task management procedure called APE. A reduction in CTM and prospective memory errors was found for both the descriptive and prescriptive groups. All operators improved in the post-training condition. Therefore, it is not clear if this is a function of learning how to use the simulator or the training of task prioritization.`

Andre, Heers, and Cashion (1995) performed an empirical study in an effort to investigate the effects of workload preview on task scheduling. They divided participants into three groups: no preview, declarative preview, and procedural preview. Pilots needed to concurrently perform the primary task of flying the aircraft as well as the scheduling and completion of three secondary tasks. All three groups were instructed to perform two flight segments. The first segment was always easy and the second segment was always more difficult (i.e., higher workload). The declarative preview group was told that workload would be manipulated and they were told the nature of the manipulation. Workload was manipulated by an increased amount of turbulence and by rearranged flight instruments so that they were no longer in the standard T configuration. The procedural preview group received the same instructions as the declarative group, but they also performed half of the practice flight during increased workload conditions. Findings suggest that pilots in both declarative and procedural groups adopted an efficient scheduling strategy. Further, procedural pilots showed the most increased benefits in flight performance. As Andre et al. (1995) showed, workload preview (specifically procedural preview) provided a benefit for scheduling strategies and for subjective workload ratings and other flight performance measures.

The Andre et al. (1995) study raises two issues that perhaps need further research so that an appropriate model of operator task scheduling can be designed. The first is that operators did not reschedule tasks in real time, but they did it per flight segment. Adams, Tenny, and Pew (1991) suggest that this behavior may be a limitation of the operator to adjust flexibly to dynamic situational demands. In contrast, Wickens (1992) suggests that such behavior reflects an efficient strategy for reducing confusion because of excessive task shifting. The second issue that needs further research is related to the type of workload preview to which the operator is exposed. The operator may be provided with internal or external preview. Internal preview means that the operator recalls from previous history, including briefings, documentation, and previous experience, whereas external preview means the operator was briefed but never actually experienced the preview. These findings suggest that pilots in both declarative (external) and procedural (internal) groups adopted an efficient scheduling strategy (Andre et al., 1995). However, Segal and Wickens (1991) found that pilots who had previous knowledge of increased future workload demands did not reschedule secondary tasks during high workload conditions (external) but that those with procedural experience did show a performance benefit (internal). This suggests that contrasting evidence may be partly attributable to the level of preview given to participants (experience versus no experience) with the change in workload. In addition, other factors related to the level of preview include the specific time in which increased workload will occur and how workload will increase (Andre et al., 1995).

Many human performance models account for the cost of time-sharing resources by adding a delay until the task reaches the top of the prioritization line (Wickens, 1989). This proposes that the assumptions about concurrent task performance in these models are based on the expected benefits and costs of task prioritization. Researchers attempting to model human task scheduling have drawn from the queuing theory literature. Queuing theory has evolved from operations management research (for a review, see Liu, 1996). Queuing theory pertains to systems that may be characterized by the ability of one or more servers attending to a group of customers lining (queuing) for service (Pew & Mavor, 1998). Carbonell and colleagues (1966, 1968) applied queuing theory to model visual scanning behavior of operators obtaining information from different displays. Their assumption was that the displays that needed to be viewed could be customers queuing for service, and the server could be seen as the operator needing to assess various displays. They then used the queuing theory to estimate operator sampling frequencies and other parameters.

Other researchers have used queuing theories to model an operator attending to multiple tasks (Walden & Rouse, 1978; Chu & Rouse, 1979; Greenstein & Rouse, 1982). These researchers assumed human attention as the server and the multiple tasks the operators had to complete as customers queuing. Using queuing theory formulas, these researchers were able to obtain information about human multi-tasking behavior, including an operator's allocation policy, the time required before a task can be attended to, and mean task execution time (Pew & Mavor, 1998).

Researchers have also borrowed from the engineering discipline in an effort to model human scheduling behavior, for instance, optimal control theory (Kleinman, Baron, & Levison, 1970; 1971). The assumption is that the performance of an experienced operator controlling a continuous system approaches that of a nonhuman optimal control system (Pew & Mavor, 1998). Various researchers have applied optimal control theory to human multi-tasking behavior (Tulga & Sheridan, 1980; Pattipati & Kleinman, 1991). As outlined by Pew and Mavor (1998), an optimal control theory of human multi-tasking behavior has the following characteristics: the system including the operators and the tasks they need to perform on the system, the task state, the decision state, noise, human limitations, a filter, attractiveness measure, and a stochastic choice model. The task state includes the state of the system as well as possible environmental elements that act on the system. The decision state pertains to the time available for the task to be completed. Human limitations act on the decision state. A Kalman filter provides true task states. The attractiveness measure calculates attractiveness for each task, and the stochastic choice model estimates the probabilities associated with working on each task. These elements are helpful in predicting minimal system error. The models yielded are generally only applicable to highly trained operators.

5.4 Effects of Task Shifting on Performance

Task shifting is an important area of research for multi-task work domains because of the costs related to shifting between tasks. Switching between tasks generally results in "shifting costs," typically an increase in response time compared to performance of the same task (Rogers &

Monsell, 1995). The investigation of task shifting performance is accomplished by a comparison of a condition or trials in which participants continually perform the same task (i.e., multiplying a set of digits by 4), with a condition or trials in which participants have to alternate between different tasks (i.e., alternate between multiplying by 4 and dividing by 4). Task shifting research provides insightful information about cognitive control functions. Knowing how the components of cognitive control function enables a designer to attempt to design a task so that it would assist the operator in using the component processes most successfully.

As far as we are aware, the workload modeling and workload management tools within IMPRINT currently do not take into account the performance costs that can be incurred as a result of shifting from one task to another, other than simply assigning a time penalty to an interrupted task that is restarted. There is a provision in the conflict matrix part of the workload model to include a non-zero value for two tasks that do not overlap at all in their resource pool requirements. Thus, for example, in MRT, a task A requiring primarily visual-spatial monitoring does not overlap in its resource demands with a task B requiring primarily response-related processing. Nevertheless, there may be a "cost of concurrency" so that the conflict matrix value for the tasks A and B can be set to value close to but not actually 0, say 0.2 (e.g., Wickens, 2002). However, this cost is different from the cost that is incurred when the operator has to shift from task A to B.

There are three main theoretical approaches to studying task shifting costs. One approach has focused on the difference between switching to the forthcoming task and shifting away from the previous task. Allport, Styles, and Hsieh (1994) had participants name the word or the color of the ink of the word from a list of words—a Stroop task. In a second set of stimuli, participants were responsible for naming either the digit value or the group size of a string of numbers (e.g., if the string of numbers consisted of 33333, participants responded group size = 5 and value = 3). Participants had to shift between the Stroop and word tasks. Allport et al. reported larger shift costs when participants had to shift from word naming to color naming and from digit value naming to group size naming. In other words, participants performed worse when they had to shift from the non-dominant task (ink color naming) than from the dominant (word reading) task because the dominant task required little effort and thus created little inertia. These results suggested proactive interference from the previous task, emphasizing the interference that automatic processing of words has on the more mentally "effortful" task of just naming. Allport et al. named this interference "task set inertia". It is thought that task set inertia or proactive interference from the previous task set dissipating function does not reflect cognitive control. Following a recent study, Allport and Wylie (1999) rejected the task set inertia assumption in favor of a retrieval hypothesis. The retrieval hypothesis suggests that interference from the previous task performance arises because of learned associations between stimuli and responses, which consequently have long-term effects on performance.

Rogers and Monsell (1995) developed another task shifting paradigm, the alternating runs task. In this approach, two tasks are described and presented in a predictable order of alternating runs (e.g., XXYYXXYY). Performance is then compared in each task: for each trial N, when the same task was completed on trial N-1 (no shifting trials: XX or YY) versus performance when tasks on trials N-1 and N differed (shifting trials: XY or YX). In the alternating runs paradigm, the shifting costs are attributable to our having to shift tasks rather than having to remember instructions for a later second task. This is compared to previous paradigms in which a complete block of task 1 was completed, followed by a complete block of task 2 with instructions given at the beginning of the experiment (Jersild, 1927). Rogers and Monsell (1995) provided a visual cue to indicate which task should be performed. This allowed for manipulation of the interval elapsing from the response in trial N-1 to the stimulus in trial N (response cue interval). Participants were presented with stimuli in a 2x2 grid that consisted of a letter and a digit. One task was to decide whether the letter was a vowel or a consonant, and the other task was to decide whether the digit was even or odd. The participants were signaled which task needed to be completed by the position of the stimulus (e.g., if the stimulus was in the left or the right portion of the upper grid, participants were responsible for deciding whether the letter was a vowel or a consonant, but if the stimulus was in the left or right portion of the lower grid, participants were responsible for deciding whether the digit was even or odd). A sample stimulus is “E1”. Additionally, the stimuli appeared in a predictable pattern of clockwise positions: upper left, upper right, lower right, lower left, and so forth.

By manipulating the response stimulus interval (RSI), Rogers and Monsell (1995) found that shifting costs became smaller as the RSI increased in duration. They concluded that participants could prepare for a shift on trial N as soon as the response to trial N-1 was complete, and if given enough time, participants would be able to “fully prepare” for the imminent task. Rogers and Monsell (1995) interpreted this preparation as an active and voluntary shift between two task sets; they called it “task set reconfiguration”. Nevertheless, Rogers and Monsell (1995) also detected a shifting cost that remained even for long RSIs. This was named the “residual shift cost”. They suggest that this shifting cost remains because “the top-down preparation that precedes a stimulus on a shift trial is endogenous, and one requires an exogenous signal (i.e., the stimulus itself) to fully prepare for the task” (Rogers and Monsell, 1995). They make a case that part of the shifting process cannot occur in anticipation of a switch but needs to occur after the participant is able to view some parts of the stimuli. It is thought that the preparatory reconfiguration component of task shifting reflects executive control success, whereas the residual component reflects executive control failure.

In an effort to examine these two opposing views of task shifting costs (active task set reconfiguration and passive task set inertia), Meiran and colleagues (1996; 2000) performed several research experiments. The stimulus consisted of a “happy face” that appeared within one of four locations in a 2x2 grid. Participants were given a cue of two arrows pointing left and right or pointing up and down. Whenever the arrows pointed left and right, the participants needed to report the horizontal position of the stimulus. Every time the arrows pointed up and down, participants needed to report the vertical position of the stimulus. By using a cue, researchers were able to manipulate the response cue interval (RCI) and the cue target interval (CTI). It was hypothesized that the RCI would affect the extent to which the task set on trial N-1 affects the response on trial N. This would mean that task set inertia consists of passive decay of an old task set. More specifically, a longer RCI should result in a weaker effect because more time has passed, resulting in a decay of the previous task set. In contrast, a shorter RCI should produce a greater effect of the previous task set. Researchers further hypothesized that the CTI should influence active task set reconfiguration processes. For instance, if the CTI is long, then endogenous reconfiguration may be complete before the target appears. This would result in no increase of response time. However, if the CTI is short, then little reconfiguration can be achieved before the target appears, and this will cause a delay before the task actually begins leading to an increased response time.

While investigating opposing views, Meiran et al. (2000) were able to reconcile the task set reconfiguration versus task set inertia perspectives on task shifting costs. They found a reduction in shifting costs as the length of the RCI increased when CTI was held constant. This supports the passive task set inertia perspective that the passing of time since the previous trial reduces its interference (Allport et al., 1994). In other words, prolonging the interval of time since the previous trial (RCI) resulted in dissipation of the previous task set. On the other hand, there was also an effect of CTI, so that prolonging the interval time from the cue to the target resulted in continued shifting cost reduction (task set reconfiguration), as purported by Monsell and Rogers (1995). This means that passive decay of previous task sets and active reconfiguration play a role in shift costs. In sum, there is now wide agreement that both active reconfiguration and passive proactive interference contribute to shifting costs, although differences of opinion remain about which factors are more influential (Allport & Wylie, 1999; Monsell, 2003a and 2003b; Altmann, 2003).

5.5 Implications for IMPRINT Workload Management and Workload Modeling

The research on workload management indicates that task prioritization is a major strategy used by operators to handle increases in task demands. Thus, the research provides good support of the current implementation of IMPRINT in which users can select different task prioritization methods. For example, a modeler could invoke strategy **D** in conjunction with variables **P**, **H**, **T**, and **S** to implement a task prioritization strategy. However, there are other ways in which task prioritization might be invoked (e.g., on the basis of other criteria, such as VACP (visual, auditory, cognitive, psycho-motor) or MRT-based thresholds for individual tasks). It is not clear whether such variable thresholding for task prioritization is possible within the current IMPRINT.

In addition to task prioritization, other task management strategies could be examined. In Funk's CTM approach, for example, other strategies include task monitoring and resource allocation. The CTM approach has received good validation in studies with pilots. Assuming that it can be extrapolated to other domains, it may be worthwhile to explore expanding IMPRINT with some of the CTM strategies.

The work of Hockey and others has indicated that a prominent strategy that operators use during overload conditions is to “protect” what they consider the primary task by expending more effort and assuming an “active control” mode. This can lead to latent performance decrements in which lower priority tasks can suffer disruptions. Moreover, Hockey suggests that there may be severe physiological costs of the active control mode, including the possibility of catastrophic breakdown (as also implied by the stress model of Hancock and Warm, 1989).

Finally, there is now a large body of empirical evidence and supporting theory for performance costs associated with shifting between tasks. The workload modeling and workload management tools within IMPRINT currently do not take into account these performance costs. This may be another area for enhancement of IMPRINT.

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