

**An investigation on subjective assessments of workload and postural
stability under conditions of joint mental and physical demands**

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AN INVESTIGATION ON SUBJECTIVE ASSESSMENTS OF WORKLOAD AND POSTURAL STABILITY UNDER CONDITIONS OF JOINT MENTAL AND PHYSICAL DEMANDS

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(ABSTRACT)

Workload is defined as the cost incurred by an individual, given their capacities, while achieving a particular level of performance on a task with specific demands. Demands of a task or combination of tasks may include maintaining postural stability, executing physical actions, and/or performing cognitive tasks. While there have been attempts to establish a physiological measure of concurrent physical and mental workload, as yet there has been no work towards developing a single subjective method of evaluation.

Select subjective assessment methodologies were evaluated quantitatively during laboratory-based experiments. Concurrent execution of mental and physical activity was required at various levels, since it was desired to be able to measure mental workload, physical workload, and also evaluate their interaction. Measurements of task performance were investigated to evaluate the effects of combined mental and physical demands and establish which subjective assessments were accurate and sensitive to changes in workload. The utility of existing subjective assessment tools created for one domain appeared to be limited when evaluating multi-task situations requiring substantial mental and physical activity.

Further clarification of the impact of different types of physical demand on cognitive processing, performance and subjective workload assessment of a constant mental task was addressed in the second experiment. This experiment investigated the effect of several activity types, specifically global versus localized effort, changes in load, and different task frequencies. The results provided support that the type of activity, load and frequency of task influence subjective mental workload assessment scores and performance. Not all existing assessment tools accurately represented an

individual's ability to perform a task when there was a combination of physical and mental demands. A unidimensional tool is suggested as a screening tool to identify situations requiring excessive or increased mental workload. Alternative methods, possibly a new multidimensional tool, should be developed to obtain more detailed information so ratings of workload for different tasks may be compared.

Effectiveness of a subjective stability assessment tool was evaluated in situations demanding mental activity while maintaining an upright posture. Tests were performed over a wide range of conditions, including various mental loads, sensory conditions, and postural stances. The purpose was to determine the effects of each task variation on the perception of postural stability. Postural sway increased with task difficulty, regardless of the source (i.e. postural stance, visual condition, mental workload). The addition of mental workload did not alter the non-linear relationship between objective measures of postural sway and perceptions of postural stability. Since decrements in balance are well perceived, subjective assessment tools may be incorporated in control strategies to minimize fall risks.

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1. INTRODUCTION

Workload transpires from the interaction between the demands of a task, the circumstances under which it is performed, and the skills, behaviors, and perceptions of the individual. Demands of a task or combination of tasks may include maintaining postural stability, executing physical actions, and/or performing cognitive tasks. The impact of these demands is in turn dependent upon the abilities of the individual performing the task. Workload is defined as the cost incurred by an individual, given their capacities, while achieving a particular level of performance on a task with specific demands (Hart and Staveland, 1988).

A fundamental focus of workload research is to determine the difference between the resources available to the individual and the demands required by the task. This conceptualization implies that workload can be changed by altering either the amount of resources available within the person or the demands made by the situation on the person (Kroemer, Kroemer, and Kroemer-Elbert, 1994; McCloy, Derrick, and Wickens, 1983).

Two common categories of workload are physical and mental. Classification is determined according to the response required or capacity to be expended (Mital and Mital, 1984). Several techniques have emerged for measuring workload, to the point where “workload” is treated as a multifaceted construct rather than a scalar quantity (Mital and Goviadaraju, 1999).

Work measurement techniques, for physical and mental work, can be broadly classified into two categories: subjective and objective. Subjective measurement techniques rely on an individual’s personal feelings and perceptions. Objective techniques rely on quantitative measures based on performance or physiology (Mital and Goviadaraju, 1999).

Measurements of mental and physical workload may be used in three different contexts: workload prediction, assessment of workload imposed by equipment and assessment of workload experienced by an individual (Wickens, 1992). Throughout system and task design, workload measurement is useful for allocating functions and tasks between humans and machines based on predictions of task interference (Hart and Wickens, 1990). Allocation may be based on a comparison of alternative equipment and

task design in terms of the workloads imposed. During task performance it may be necessary to monitor operators of complex equipment to adapt the task difficulty or allocation of functions in response to increases and decreases in workload (Wickens and Gopher, 1977). Choosing operators who have higher workload capacities for demanding tasks may be imperative for efficient performance of some tasks.

Physical and psychological factors of work performance operate jointly in cueing muscular and cardiovascular effort in response to feelings of balance, workload, exertion, and fatigue (Fleishman, Gebhardt, and Hogan, 1984). An individual's subjective report of perceptions associated with maintaining balance, physical work or mental work can be used to obtain information about physiological responses to work and workload level. This subjective reporting suggests that evaluating perceptions of work effort, in relation to the performance of job tasks, might serve as a basis for a job-analysis method relevant to physically and mentally demanding tasks (Fleishman et al., 1984).

Many subjective (psychophysical) methods have been developed that have been used to determine physical and mental workload. Psychophysical techniques are based on the relationship between a stimulus and an individual's reaction to it (Matlin and Foley, 1997). These techniques are often used in conjunction with other objective and subjective methods to determine the workload associated with a particular task or job. Relatively little research, however, has investigated measurement of *concurrent* physical and mental workload. Furthermore, there have been few investigations of the interaction between the types of workload and their possible mutual effects. Figure 1 is a conceptual representation of the factors involved when attempting to measure workload.

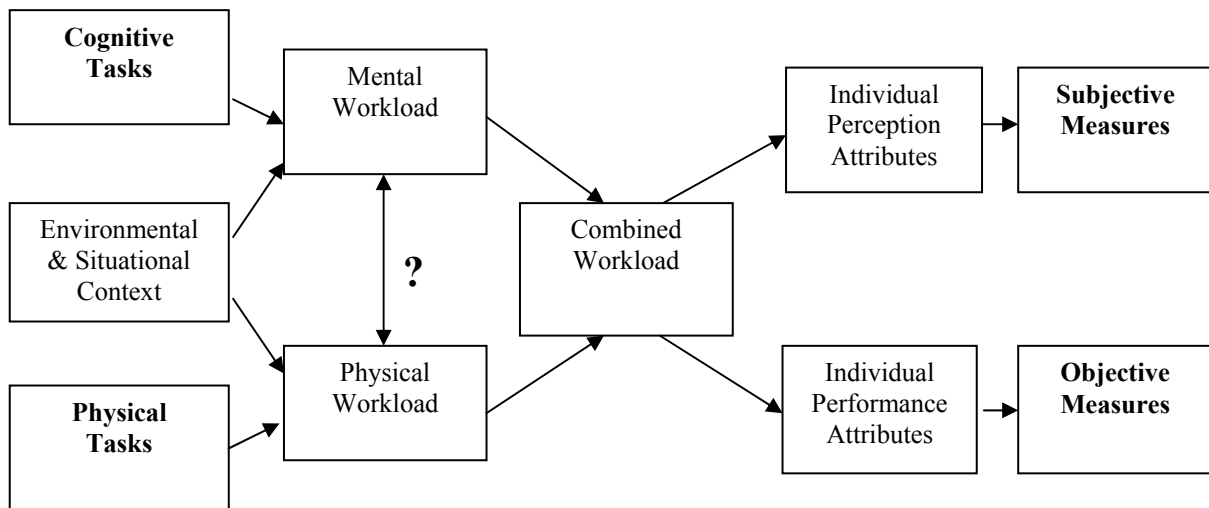


Figure 1. Conceptual representation of workload measurement.

Subjective workload estimates and objective measures of physiological changes within the cardiovascular or respiratory systems are typically compared to evaluate existing assessment tools. The accuracy of techniques used for measuring subjective mental workload is also often confirmed using other subjective mental workload assessment techniques. It should be noted that the impact of physiological parameters on perception depends on their availability for conscious monitoring during physical activity (Mihevic, 1981). Relating the measures and these parameters over a wide range of conditions, including extreme workloads and environmental conditions, and varying mental workloads, defines the level of correspondence and generality of the subjective methods.

Individuals are expected to perform physically demanding tasks, including maintaining postural stability, concurrent with cognitive responsibilities, particularly with the ongoing implementation of technology (e.g. infantry soldiers, construction workers, aircraft mechanics). Validity and reliability of existing workload assessment methods have not been evaluated in situations demanding both mental and physical efforts, particularly in extreme conditions and varied environments. Given the new demands and expectations being placed on individuals during complex task performance, the impact of physical effort on cognitive performance is a vital aspect of determining combined

workload levels. Because of their ease of use, psychophysical scaling measures are of predominant interest for workload assessment, and it is critical to review their value in determining physical and mental workload for a given task.

There are many issues that must be addressed in the developmental stages of each design feature for any system, particularly aspects of the task that require combining mental and physical demands. Type of information, complexity of tasks and distraction can be expected to affect an individual's ability to perform tasks with speed and accuracy. Personnel who are overworked will shed tasks until they achieve a level they can manage (National Research Council, 1997). Technology can and should be used to reduce this workload, not increase it. A tendency during the design process is to provide a maximum amount of information, yet too much information or poor presentation of the information can contribute to inefficient and degraded task performance.

The development of efficient and effective systems is not based solely on the amount of information provided, but requires an understanding of how individuals process the information that is presented to them during a task. This is particularly important if the task utilizes multiple resources or cognitive processes. An ability to share resources and perform concurrent tasks is critical for many jobs and is strongly related to the workload imposed by various tasks. Human information-processing theories imply that concurrent tasks can be performed successfully if the combined workload does not exceed total capacity of the individual and that the tasks do not use the same resources (Wickens, 1984a).

Research in the area of attention and information processing has yielded theories and models to explain how an individual receives information and produces a response when multiple task demands are present. During the performance of any task, individuals receive a wealth of information from their senses (mental and physical). The information received becomes the input for the cognitive processing while the action performed by the individual comprises the response. Responses reflect how individuals allocate resources and what decrements occur due to prioritizations.

The proposed research examined concurrent tasks, investigated the ability of individuals to perform the tasks, and determined whether workload could be effectively assessed using existing subjective measures. Interactive effects of physical and mental

workload on subjective workload assessment were investigated in the first experiment. Measurements of task performance were evaluated to establish which subjective assessments were most accurate and easily obtained. In addition, the sensitivity of common subjective mental workload techniques to changes in physical workload was determined. Further clarification of the impact of different dimensions of physical workload on cognitive processing, performance and subjective mental workload assessment of a constant mental task was addressed in the second experiment. Objective measures of postural sway and subjective assessment of postural stability were the focus of the last experiment. Effects of mental demands on these measures were considered.

2. REVIEW OF LITERATURE

2.1. Psychophysics

2.1.1. Historical Developments of Psychophysics

Psychophysics is a branch of psychology concerned with the relationships between sensations in the psychological domain and their physical stimuli (Gescheider, 1985). The underlying theory assumes that the strength of a sensation is directly related to the intensity of one or more physical stimuli (Stevens, 1975). Psychophysical scaling/rating methods and measures, particularly related to task analysis, are of practical utility towards assessing and quantifying workload during various tasks in diverse environments. An important benefit of the psychophysical method is its relative ease of implementation; evaluations can be performed during actual task performance, on large groups concurrently, and without a need for complex instrumentation.

Despite wide development and application of psychophysical methods, they are not universally accepted as suitable means to objectively evaluate mental and physical workloads. The concept of stimulus intensity is comparable to the concept of task characteristics (or task and environmental characteristics combined), and therefore, judgments of workload are similar to judgments of stimulus intensity. This is more easily seen in judgments of physical workload, but would seem also to be true of mental workload. Concerns include the level of reliability, influence of motivation, variability across individuals that precludes a common reference or anchor point, and unknown relationships between subjective assessment and biomechanical-physiological workloads. The latter concern is of particular interest. There is good evidence that mechanical and metabolic stress can be used to predict illness and injury, and that maximal physical capabilities can be reliably measured or estimated (Borg, 1982). Whether subjective measures can provide relevant information towards the reduction of injuries, however, has not been established.

2.1.2. Classical Psychophysics

Classical psychophysicists, Weber and Fechner, were interested in measuring levels of detectability of a sensory stimulus or a change in the stimulus (Noble and

Robertson, 1996). Central to psychophysics is the concept of a sensory threshold, where events have to be stronger than some critical amount in order to be consciously experienced (Gescheider, 1985). The *absolute threshold* or *stimulus threshold* is the smallest amount of stimulus energy necessary to produce a sensation (Gescheider, 1985). The *difference threshold* is the amount of change in a stimulus required to produce a just noticeable difference (JND) in the sensation (Gescheider, 1985; Noble and Robertson, 1996). Much work in psychophysics has consisted of investigating how the absolute and difference thresholds change as some aspect of the stimulus (wavelength, frequency, adaptation time, intensity level, weight, etc.) is systematically varied.

Classical psychophysicists developed three measurement methods to study human perception and measure physical stimuli. The *method of limits* primarily determines the absolute thresholds. Judgments of equality with a standard are made using the *method of adjustment*. The third method, the *method of constant stimuli*, determines both absolute thresholds and difference thresholds (Noble and Robertson, 1996).

Psychophysics attempts to determine the functional relationship between psychological sensations and stimuli in the physical domain (Fechner, 1966). Weber believed that human perceptions followed psychological laws. He postulated that for a change in stimulus to be just noticeable, a fixed percentage must be added (Stevens, 1975). In 1834 he proposed what is now called Weber's Law. It states "that the just noticeable difference grows larger in direct proportion to the size of the stimulus" (Noble and Robertson, 1996; Stevens, 1975).

Fechner (1966), described psychophysics as the theory of the functionally dependent relations of the physical and the psychological worlds. He published *The Elements of Psychophysics* in 1860, which expanded on Weber's research and examined the relationship between that which we perceive and stimuli present in the world (Gescheider, 1985). Fechner's research could not confirm the linear relationship stated by Weber (Noble and Robertson, 1996; Stevens, 1975). Instead, he believed that for each JND added to a stimulus, the sensation increases by an amount of a constant size (Stevens, 1975). Therefore implying that all JND's represent equal increments in sensation magnitude. Fechner's equation was considered the first psychophysical law (Gescheider, 1985). A combination of ideas proposed by Weber and Fechner led to the

development of a logarithmic law for the escalation of sensation that more accurately represents the relationship between sensations and physical stimuli (Stevens, 1975).

2.1.3. Modern Psychophysics

Study of perception is the central focus of classical psychophysics. Modern psychophysics, which dates back to the early 1930s, focuses instead on the sensory response rather than the stimulus or change in stimulus. Measurements are obtained directly from the sensation, rather than derived from the measurements of the physical stimulus. Stevens, by studying sensory processes, is considered to be the father of modern psychophysics, for example, by Noble and Robertson (1996). Work by Stevens led to the rejection of Fechner's law and the development of a general power law relating the level of sensation to the power of the stimulus. Although sensation grows with the power of the stimulus, each stimulus dimension was found to have a different power function (Stevens, 1975). Psychophysics relates raw stimuli to perception but is independent of cognitive requirements.

Scaling of sensations is the primary focus of modern psychophysics. Scaling is defined as "the use of numbers to differentiate among objects or events" (Noble and Robertson, 1996). Several types of scales exist that can be adapted for measurements of perception: nominal scales, ordinal scales, interval scales, and ratio scales. Ratio scales, in contrast to the alternatives noted, contain an absolute zero and provide numbers that can be used to make ratio statements. Ratio scales are also thought to provide a maximum amount of information; therefore, they are the most utilized within the area of psychophysics (Noble and Robertson, 1996; Stevens, 1975).

2.2. Information Processing

Information processing involves psychological processes and specific patterns of informational flow (Uttal, 1981). Theories and models have been developed to explain the flow of information. Although the specifics of the theories vary, it is generally believed that humans have limited mental capacities. Thus, there is a limit to the number of items that can be attended to at one time (Matlin and Foley, 1997). Individuals may have to be selective in determining what to attend to and vary concentration or the

amount of mental effort designated for the task (Kahneman, 1973). Current motivations and intentions determine the voluntary effort exerted to focus on particular activities.

When performing mental tasks, different mental operations (e.g. perceiving, rehearsing, and responding) must be carried out, and performance of each requires some degree of the individual's limited processing resources. Since resources are limited, time-sharing may be required. Divided attention occurs when two or more tasks must be performed simultaneously and attention is required for the performance of all tasks. Irrelevant stimuli are filtered and disregarded while attention is divided to accommodate parallel processing of pertinent items (Kahneman and Treisman, 1984).

Some operations may require resources that are different from others. As a consequence, there is less competition between these processes for their enabling resources, and time-sharing between them may be more successful (Wickens, 1984a). Automatic processing, achieved with experience and practice, may also enhance simultaneous performance of tasks. An automatic task occurs outside of voluntary control and is independent of attention (Bargh and Ferguson, 2000; Hasher and Zacks, 1979; Logan, 1980; Regan, 1981). Allocating attention to an automatic task provides no benefit and performance is not impaired when attention is required elsewhere (Kahneman and Treisman, 1984).

Several mechanisms determine the success or failure to complete a group of tasks. Scheduling and efficient switching between activities are important ingredients to success. If enough time is not provided to complete the tasks serially, the individual may be forced to engage in concurrent processing. The effectiveness of multi-task performance is determined by the similarities of task elements, cooperation between task processes, and competition for task resources. Additionally, a critical element of multi-task performance is the difficulty of the tasks (Wickens, 1984a). A number of different theories and models have been developed in an attempt to explain how an individual processes the inputs for more than one task. Models based on single-resource theory do not consider the structural aspects of the tasks being analyzed (e.g. task composition, modalities, and required resources), whereas multiple-resource models generally account for the structural characteristics of both the task and of the human operator (Wickens, 1984a; Wickens, 1989; Wickens, 1991).

2.2.1. Single Resource Theory

Humans are proposed to be a single-channel processor of information. This theory was originally developed by Craik (1947). The theory stipulates that each individual has a limited processing capacity, with the cognitive mechanisms required to perform tasks and mental activities viewed as a single pool of resources (Moray, 1967). This capacity could be allocated in graded amounts to various activities depending on their difficulty or demand for resources. This concept emphasizes the flexible and sharable nature of attention or processing resources.

All tasks and mental activities share the same resources. Task demands increase either by making the elements of the task more difficult or by imposing additional responsibilities; in response, physiological arousal mechanisms produce an increase in the supply of resources. Even so, as task demands increase, the available resources may be insufficient to compensate for the additional resource demands. Thus, limited resources coincide with decreased task performance.

Task performance is dependent on the amount of resources that are allocated to the task and can be defined more formally by means of a performance resource function. Norman and Bobrow (1975) developed a performance resource function to relate the quality of performance to the quantity of resources invested in a task, given that two tasks share the same resources. The most favorable situation is during single-task performance when all resources are invested in the task. Performing a concurrent task diverts resources away from the original task and possibly degrades performance. The effect of the additional task depends on the characteristics of each task. A task is *data-limited* if performance is maximized by the quality of the data, not by the resources invested. Alternatively, if performance is altered with added or depleted resources, the task is *resource-limited*. This and similar theories assume that individuals have the ability to adapt during multiple task situations and allocate resources between tasks. Gopher et al. (1982), Gopher and Navon (1980) and Wickens et al. (1983b) have demonstrated the existence of this ability in multiple task situations.

The concept of the performance resource function was extended by Norman and Bobrow (1975) and Wickens and Yeh (1985). The relationship between two tasks that are performed concurrently is referred to by means of a performance operating

characteristic. Performance operating characteristics relate performance as a function of the amount of resources allocated to each task. These curves combine two performance resource functions for data-limited tasks to summarize a number of characteristics of two time-shared tasks. Performance resource functions and performance operating characteristics can be used to provide information regarding single-task performance, time-sharing efficiency, extent of shared or exchangeable resources, allocation bias, and the effects of automaticity and practice (Wickens, 1984a).

Investigations of situations requiring the execution of concurrent tasks have identified limitations to single-resource theory. The resources required to perform a task are partially determined by the difficulty of the task. Additional resources are required for tasks of greater difficulty performed at the same level of performance. Yet, interference between tasks is not solely determined by the difficulty of the tasks, but by their composition (e.g. modalities required for processing) (Wickens, 1984a).

2.2.2. Kahneman's Capacity Model

Kahneman (1973) extended single-resource theory by suggesting that there is a single undifferentiated pool of resources. He describes a capacity model to explain cognitive processes during multi-task situations and allocation of capacity to mental activity. This model assumes that there is a general limit on an individual's capacity to perform mental work. In addition, it asserts that individuals can allocate this capacity among concurrent activities. Activities fail or performance degrades because the demands of the tasks are beyond the capacity of the individual or because the allocation policy channeled available capacity to other activities.

Kahneman (1973) distinguishes between structural and capacity interference to explain why tasks that use common structures interfere more than would be predicted on the basis of their capacity demands alone. Kahneman's Capacity Model complements structural models that limit concurrent activities if the same mechanism is required to carry out two incompatible operations at the same time (e.g. sequential verbal responses are necessary due to the existence of only one tongue). Therefore, as long as the two tasks can be performed at the same time, the capacity model does not differentiate between types of processing and resources that are necessary to complete the tasks.

When the supply of attention does not meet the demands, performance falters, or fails entirely.

Completion of a mental activity requires two inputs: information specific to the structure of the task and nonspecific input (i.e. capacity, attention, effort). The ability to do multiple tasks depends on the complexity of each task. A difficult or complex task demands more effort than an easy task. The ability to perform simultaneous activities is limited when the activities require more mental effort than is available.

All mental activities compete for a limited pool of attentional resources. Allocation of resources is partially voluntary. The allocation policy described in Kahneman's model is controlled by four factors: (1) enduring dispositions that influence involuntary attention; (2) momentary intentions; (3) evaluation of demands; and (4) effects of arousal (Kahneman and Treisman, 1984). Given a set of possible activities, the model describes the factors influencing the responses (Figure 2).

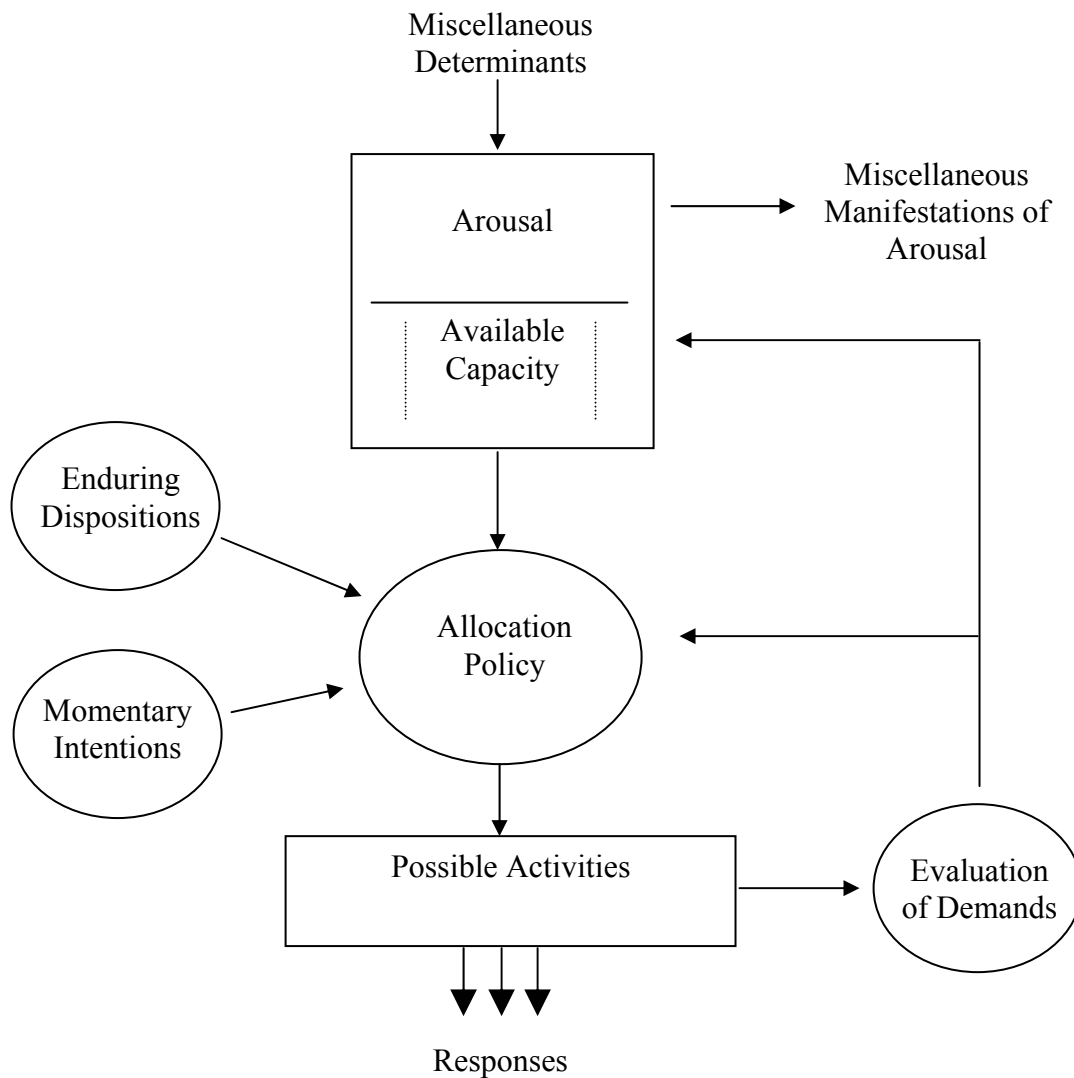


Figure 2. Kahneman's Capacity Model for attention (adapted from Kahneman, 1973).

At maximum capacity and allocation of attention, performance can still be disrupted by external circumstances. These situations compete for attention and are referred to as enduring dispositions, for example, involuntary responses to unexpected motion or noise. Individuals instinctually respond to such stimuli, reducing attention to other tasks. Allocation of attention is also impacted by momentary intentions. Particular objectives requiring focused attention or distracting extraneous thoughts may influence attention available for other tasks. The evaluation of demands controls the supply of

capacity, as determined by the tasks that the allocation policy has selected. During a task individuals monitor success and failure. If attention is exceeded and failure is detected, action is taken to reduce demands (e.g. shedding tasks). Arousal and capacity change according to demands of current activities. The magnitude of attentional resources is not constant and can be made larger or smaller depending on arousal, motivation, level of anxiety and alertness. Voluntary application of attentional resources is more effective when physical and mental disruptions, caused by symptoms of anxiety or distraction (miscellaneous manifestations of arousal), are reduced (Kahneman and Treisman, 1984).

Kahneman's Capacity Model (Jorna, 1992) illustrates how an individual can control or at least influence the attentional processes. It also provides insight into how the system can fail. Regardless of arousal and allocation of resources, if the activities required by the system exceed the limits of attention for that individual, performance will degrade.

2.2.3. Multiple Resource Theory

The human information-processing system appears to utilize several kinds of resources that allow time-sharing to be more successful (Navon and Gopher, 1979). Multiple-resource theory argues that instead of one single supply of undifferentiated resources, individuals have several different capacities with resource properties (Wickens, 1984a). The theory does not necessarily predict that tasks using separate resources will be perfectly executed, but only that time-sharing efficiency will improve if the tasks require different resources (Wickens et al., 1983b).

Multiple resource theory assumes that information flows through channels and that there is a limited capacity to attention based on the resources available. Channels define the flow of information through some or all of the stages of processing, and they are characterized by some distinct perceptual property. Individuals may process information along multiple channels in parallel (concurrent) or consecutively (sequentially). The term capacity refers to a maximum or upper limit of processing capability for each channel. Capacity differs from resources, as resources represent the mental effort supplied by the individual to improve the processing efficiency along a channel or the performance of a mental operation (Wickens, 1984a).

When tasks are combined, the efficiency of their time-sharing is dependent on the extent that they use different resources. The multiple resource model developed by Wickens (1980; 1984b) proposed three dichotomous dimensions that have been defined to account for the differences in time-sharing efficiency. The levels within the dichotomies use different resources (Wickens, 1984b; Wickens, 1992). Figure 3 lists the three dichotomous dimensions and provides examples of tasks or task components that illustrate each kind of resource (Wickens, Gordon, and Liu, 1998). Figure 4 provides a dimensional representation of the multiple resources and their interactions (Wickens, 1984a).

1. Processing Modalities (auditory versus visual)
2. Processing Codes (spatial versus verbal)
3. Processing Stages (perceptual/cognitive processes versus response)

Perceptual/Cognitive			
	Perceiving	Central Processing	Response
Verbal	print	rehearsal	voice
	speech	mental arithmetic	
Spatial	analog quantities	mental rotation	manually guided
	spatial patterns	imagining	response

Figure 3. The three dichotomous dimensions of multiple resource theory and examples of tasks defined by codes and stages (adapted from Wickens et al., 1998).

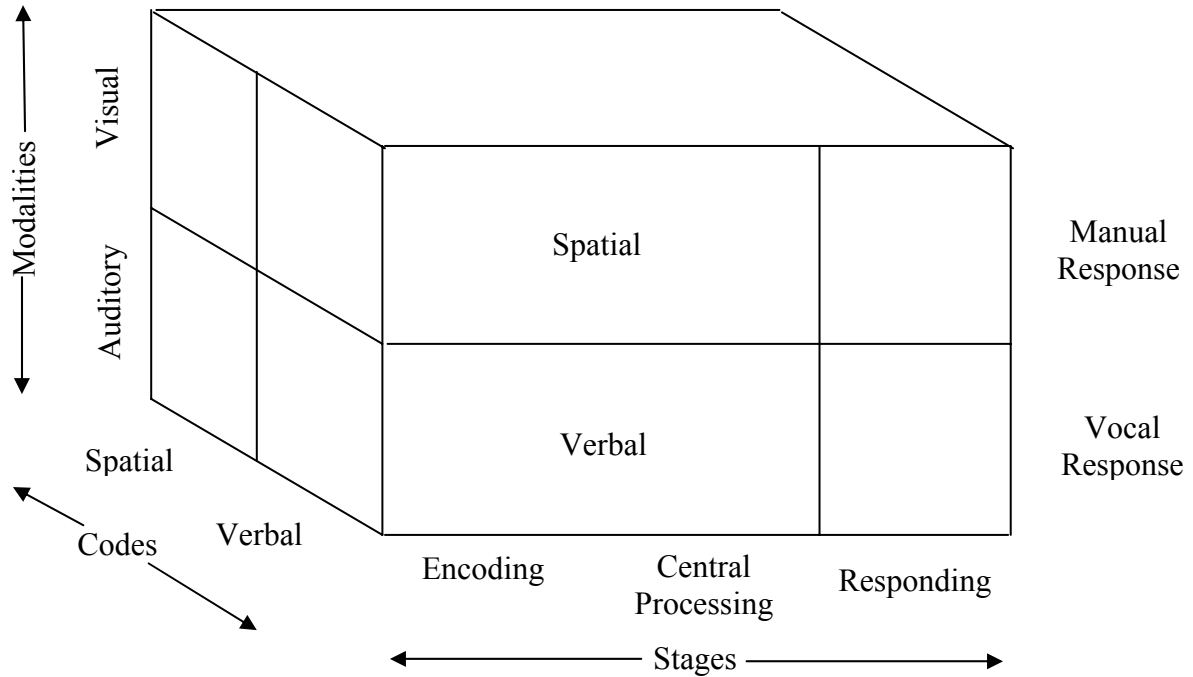


Figure 4. A dimensional representation of the three dimensions of multiple resource theory and their interactions (adapted from Wickens, 1984a).

If resources are shared, tasks will interfere with each other and difficulty-performance trade-offs will be more likely. In general, cross-modal time-sharing is better than intramodal and should be implemented whenever possible (Wickens, 1984a). While two tasks demand separate rather than common resources on any of the three dimensions, three phenomena will occur: (1) time-sharing will be more efficient; (2) changes in the difficulty of one task will be less likely to influence performance of the other; and (3) resources withdrawn from one task will not be used to advantage by the other since it depends on different resources (Wickens, 1984a).

The resources used for perceptual and central-processing activities appear to be the same, and they are functionally separate from those underlying the selection and execution of responses. Shallice et al. (1985) determined that tasks involving speech recognition (perception) and production (response) do not utilize similar resources. Further research indicates that spatial and verbal processes, or codes, whether functioning in perception, working memory, or response, depend on separate resources. Manual

control may disrupt performance in a task environment imposing heavy demands on spatial working memory, whereas voice control may disrupt performance of tasks with heavy verbal demands (Wickens, 1984a). Therefore, manual tasks, such as tracking, can be performed in combination with cognitive tasks, such as mental arithmetic. In general, any spatial task can be combined with a verbal task.

The three dimensions of Wickens's multiple-resource model are not intended to account for all structural influences on dual-task performance and time-sharing efficiency. However, stages, modalities, and codes do represent three major dichotomies that can account for a significant portion of these influences and can be readily used in predicting task interference. Furthermore, the loadings on these dimensions can be easily established during the design process. Thus visual, auditory, print, and speech input channels are easy to define, as are voice versus manual controls. Task analysis can determine the extent of linguistic requirements in working memory and demands on the perceptual and cognitive systems (Wickens, 1984a).

Multiple-resource theory provides information about which types of tasks can be performed simultaneously. Task taxonomies and other categorization systems can be used to describe the personnel characteristics and skills required by a task (Fleishman, 1978). Systems engineers can then design tasks such that the performance of similar tasks is not required concurrently. In addition, these categorizations can be used to assess the required workload capacity of an established task. For example, combining two tracking tasks may be ineffective due to a high demand of a particular resource. Multiple-resource theory also identifies possible inefficient use of resources and provides clues concerning the effectiveness of an individual's workload capacity.

2.2.4. Baddeley and Hitch Working Memory Model

Theories regarding information processing have been developed that emphasize the importance of memory. Baddeley and Hitch (Baddeley and Hitch, 1974) proposed the idea of a working memory to explain information processing during concurrent tasks. Working memory is defined as a set of linked and interacting information processing components that maintain information in a short-term store (or retrieve information into

that store) for the purpose of the active manipulation of the stored items (Becker and Morris, 1999).

The Baddeley and Hitch Working Memory Model is characterized by the executive as a system for sharing resources between processing operations and temporary storage (Baddeley and Hitch, 2000). Working memory, according to Baddeley and Hitch (1974), consists of a central executive that is responsible for initiating control and decision processes, and which is assisted by a number of subsidiary slave systems, including the articulatory (phonological) loop and visuospatial sketchpad (Salame and Baddeley, 1982). The articulatory loop holds and manipulates speech-based information, while the visuospatial sketchpad holds and manipulates visual images (Baddeley, 1996). The central executive is also responsible for the transmission of information between short-term memory to long-term memory (Baddeley and Della Sala, 1996; Kemps, De Rammelaere, and Desmet, 2000). A conceptual diagram of the Baddeley and Hitch Working Memory Model (Baddeley and Hitch, 1974) is shown in Figure 5.

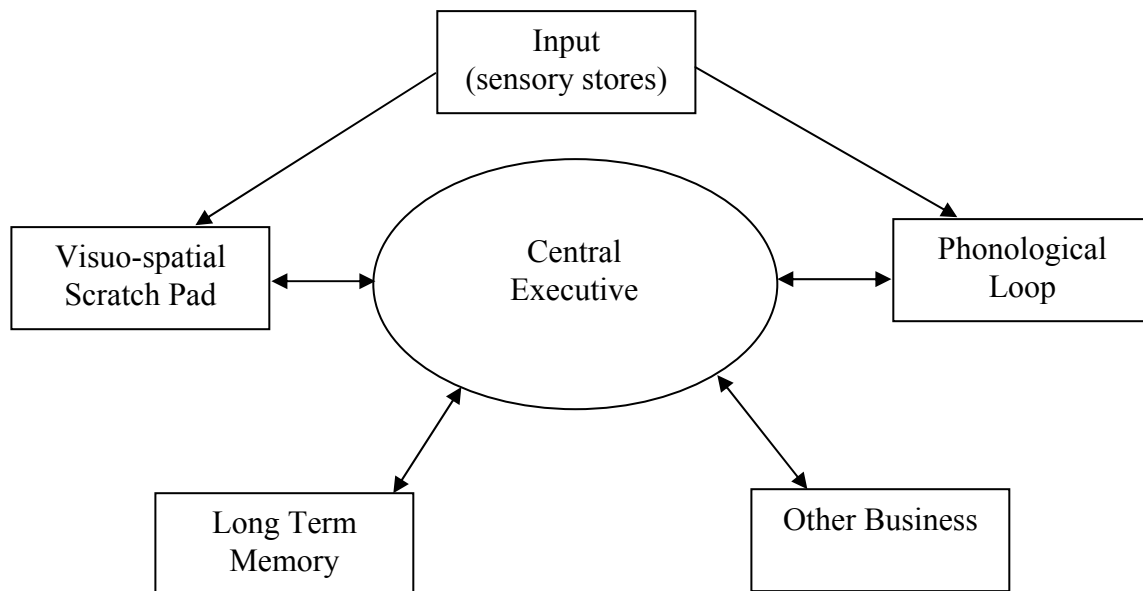


Figure 5. A conceptual diagram of the Baddeley and Hitch Working Memory Model (adapted from Baddeley and Hitch, 1974).

Expansion of the working memory model has been explored. A third subsidiary system, called the episodic buffer, has been added (Baddeley and Hitch, 2000). The

episodic buffer acts as a temporary storage system capable of holding information from the slave systems of working memory and long-term memory in some form of multimodal code. It is assumed to be controlled by the central executive, and allows access through conscious awareness (Baddeley and Hitch, 2000).

The main responsibility of the central executive is to integrate the information received from the subsidiary systems and long-term memory. Therefore, the central executive is at the center of the model. The central executive behaves as a supervisor that coordinates cognitive functions, playing a significant role in attention, planning, and controlling behavior. It also dictates selection, initiation and termination of processing routines (Kemps et al., 2000).

As the attentional controller, the central executive selects certain streams of incoming information and rejects others (Baddeley and Della Sala, 1996). Due to a limited capacity, the functions of the executive control include selective attention, the capacity to focus attention on one stream of information while shutting out irrelevant material and to switch attention from one source to another.

Since all tasks require some level of physical and mental capacity, the central executive is continuously employed to determine the allocation of resources based on the priority level of the task. The central executive receives information from all of the subsidiary systems and has to integrate the information. Each part of a task will be allocated a priority level by the individual, with resources distributed initially to the primary task with the highest priority. Any resources remaining will be allocated to the secondary task (Baddeley, 1986; Baddeley, 1990).

The attentional control mechanism of the central executive has been fractionated into the capacity to focus attention, switch focus, and to divide attention across two concurrent tasks. Dual-task performance has been used recently to support fractionation (Baddeley and Hitch, 2000). The dual-task paradigm is widely used in working memory studies as a way to study the processes used for encoding, maintaining, or retrieving information. It is used to demonstrate the separability of the memory systems responsible for learning by means of visuospatial imagery and of learning by rote repetition (Baddeley, 1992). The principle is that if a given process is used in the primary task, it

should be interfered with when a secondary task also relies on that same process (de Ribaupierre and Bailleux, 2000).

An underlying assumption in the use of dual-tasks is that the individual's capacity will be divided between the two tasks. Specifically, as the difficulty or priority of one task increases, an increased amount of resources will have to be allocated to that task in order to maintain a particular level of performance. If the two tasks utilize the same limited resources, allocating more resources to one task necessarily leaves less for the other (Baddeley and Della Sala, 1996). Thus, as the difficulty or priority of one task increases, performance of the other should degrade.

There are difficulties with the dual-task method. The concurrent performance of two tasks increases the complexity of the combined task, as compared to the individual tasks. As a consequence, the decrease in performance, which is observed in the primary task in the dual condition relative to the single condition, may result from this increase of complexity rather than from interference with a particular process (de Ribaupierre and Bailleux, 2000). The effectiveness of task performance relies on the ability of the individual to allocate sufficient resources to both tasks and switch attention efficiently. The central executive attempts to access and manipulate all necessary information, but increased difficulty will limit the information that can be processed, and performance will suffer since the central executive will have to disregard any information beyond its limited capacity.

2.2.5. Executive Process-Interactive Control

Computational models are another approach used to explain the information processing that takes place during the performance of tasks by modeling human multi-modal and multiple-task performance. Cognitive architectures are theoretical structures and mechanisms for human cognition, within which models for specific tasks can be constructed (Kieras and Meyer, 1997). The Executive Process-Interactive Control (EPIC) is an example that is useful as a research system for exploring human performance limitations that determine the effects of a particular design (Kieras and Meyer, 1997).

The purpose of EPIC is to represent the perceptual, motor, and cognitive constraints on the human ability to perform tasks (Kieras and Meyer, 1997). EPIC architecture consists of components that imitate various functional parts of the human information-processing system. There are separate processors for the hands, eyes, and vocal organs. EPIC and its task environment provide a basis for realistically simulating multiple-task performance where all processes can be simultaneously active (Meyer and Kieras, 1997).

EPIC is designed to integrate mechanisms for basic information processing and perceptual-motor activity with a cognitive examination of procedural ability. Thus, EPIC has a production-rule cognitive processor surrounded by perceptual-motor peripherals. A conceptual representation is presented in Figure 6 (Kieras and Meyer, 1997; Meyer and Kieras, 1997). Applying EPIC to a task requires specifying both the production rule programming for the cognitive processor and the relevant perceptual and motor-processing parameters (Kieras, Wood, and Meyer, 1997). EPIC's cognitive processor consists of three major subcomponents that interact to enable a high degree of parallel processing. The components are the on-line declarative working memory, procedural memory, and production-rule interpreter (Meyer and Kieras, 1997).

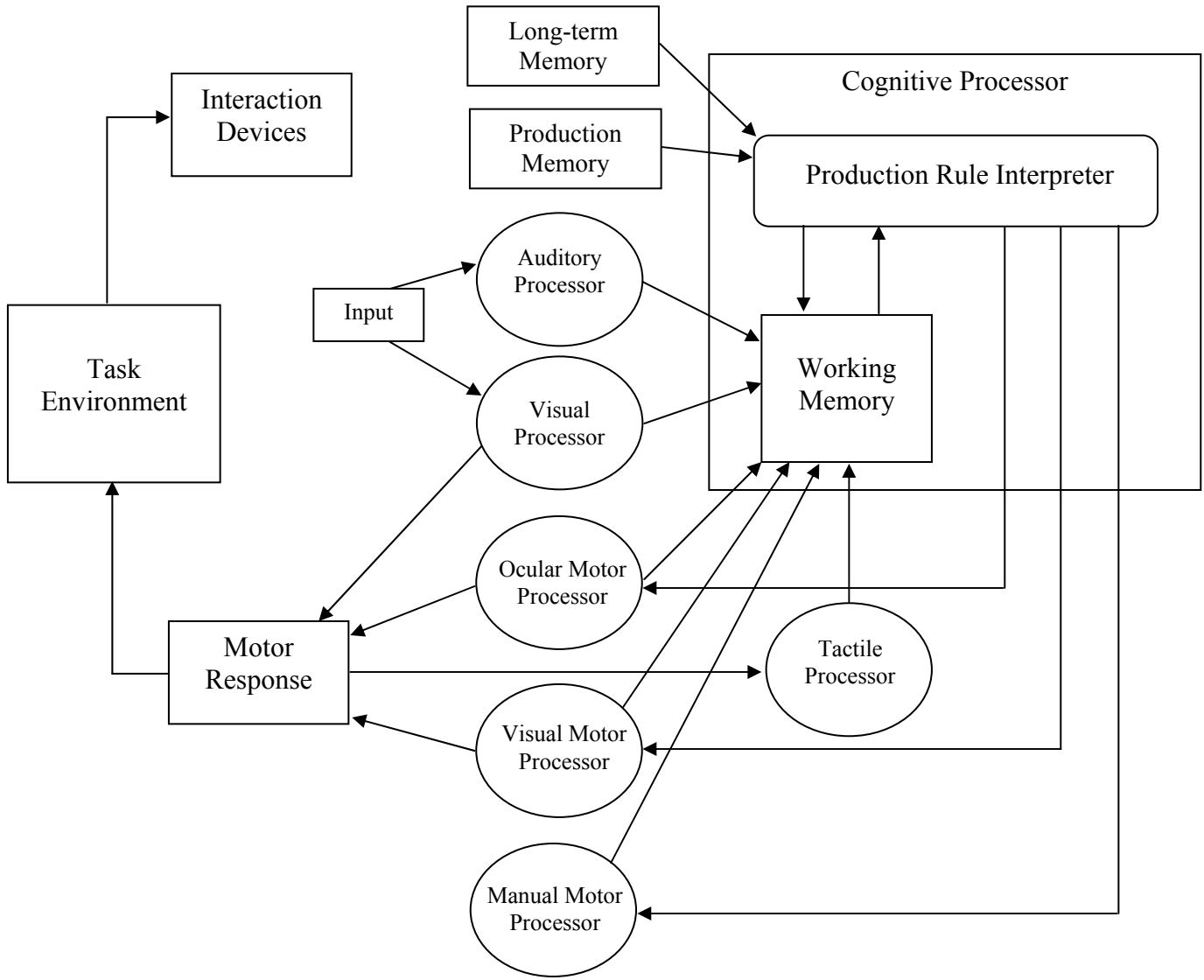


Figure 6. A conceptual representation of the Executive Process-Interactive Control (EPIC) cognitive architecture (adapted from Meyer and Kieras, 1997).

The production-rule interpreter of the cognitive processor applies task and executive rules by using a parsimonious production system (Meyer and Kieras, 1997). Information in the cognitive processor evolves systematically over time, and allows the performance of one or more tasks to proceed efficiently from start to finish. Performance is achieved by applying production rules having the form “IF X THEN Y,” where “X” refers to the current contents of working memory, and “Y” refers to actions that the cognitive processor executes. The actions of the rules are executed whenever working

memory contains the entire item in the rule's conditions. In addition, the rule instructs the manual motor processor to add and delete specified items in working memory, as they are needed (Meyer and Kieras, 1997).

Unlike either single- or multiple-resource theory, the EPIC architecture assumes that there is no limit to how many production rules can have their conditions tested and actions executed during any particular processing cycle. Therefore, the ocular, manual, and vocal motor processors can all be operating simultaneously. Each processor constitutes a single-channel mechanism that allows a limited rate of movements within a particular motor modality (Meyer and Kieras, 1997).

The EPIC architecture is used to formulate computational models of human multiple-task performance in terms of production-rule sets (Kieras et al., 1997). These rules guide the operation of the cognitive processor. For each task, a distinct set of production rules must be specified that explain how the task is to be performed. Various components of the architecture will be used and must be incorporated into the rules. Supervisory executive processes require the specification of detailed production rules. Rules may change over time, depending on the particular task combinations, priorities, and subjective strategies that are involved (Kieras et al., 1997; Meyer and Kieras, 1997). Finally, models are evaluated computationally by simulating multiple-task performance conditions that mimic those in which empirical data have been collected (Meyer and Kieras, 1997).

EPIC can be applied to many types of tasks, including those involving physical and mental demands. To achieve the desired performance goals, the executive process coordinates the use of the perceptual, cognitive, and motor resources of the system so that the tasks can be executed while applying the appropriate priority and speed. Executive processes utilize the parallel processing capabilities of the three processors to complete all desired tasks (Kieras and Meyer, 1997).

2.2.6. Critical Interpretation

Several theories and models have been developed to explain information processing mechanisms required during multiple task performance. The tasks being performed determine the sensory inputs. The level of interference created between

concurrent tasks depends on many factors and affects the workload experienced for task completion. Although similarities do exist among current information processing theories, conclusive evidence has not been produced to determine which theory most appropriately describes the cognitive processes involved in completing concurrent tasks requiring different resources.

Multiple-task interference occurs due to resource competition. Identifying the resources required to complete a task is of fundamental importance to the measurement of workload and performance. The approach used by an individual to process multiple inputs, however, influences subjective assessment levels. An accurate information processing theory can be used during system and task design to predict multiple-task performance imposed by the system or task environments (Wickens, 1984a).

The current theories involve multiple channel processing systems, including parallel distributed processing. Single channel processing theories are no longer considered.

2.3. Mental Workload Assessment

A satisfactory consensus of the factors that determine mental workload levels, have yet to be clearly presented in the literature. “Mental workload is intrinsically complex and multifaceted” (Jex, 1988, p.9). Evidence exists that there is a relationship between mental workload and stress, but the two terms are not synonymous. Mental workload refers to the processing that is required to perform a task given the resources available to the individual. Although stress also refers to the relationship between environmental demands and availability of resources, demands originate from the total environment. Stress is any circumstance that threatens or is perceived to threaten adaptation and ability to cope with demands (Lazarus, 1990). Demands can be physical, psychosocial or organizational. Mental workload research attempts to specify the limits of the processing capacity of the individual, whereas stress research examines the factors in the work environment that produce negative effects (Gaillard, 1993).

There is no direct method for measuring mental workload; instead, several indirect measures have been developed (objective and subjective). Common categories of indirect mental workload measurement techniques include: (1) physiological measures

(e.g. heart rate, heart rate variability, and brain activity), (2) performance measures (e.g. reaction time, number correct, and number detected), and (3) subjective procedures that include subjects' estimations of workload (Lysaght, Hill, Dick, Plamondon, Linton, Wierwille, Zaklad, Bittner Jr, and Wherry, 1989; O'Donnell and Eggemeier, 1986; Tsang and Wilson, 1997). None of these techniques are a pure measure of mental workload, with each contaminated by other factors. It is usually recommended that the most effective approach is to combine two or more of the above techniques. Commonly used methods and tools for measuring mental workload are presented below.

2.3.1. Physiological Measures

Physiological measurements have made a significant contribution to the assessment of mental workload (Takano, Nagasaka, and Yoshino, 1992). They are believed to represent mental workload levels because information processing involves the central nervous system, and the physiological manifestations of this nervous activity can be measured (Hancock, Meshkati, and Robertson, 1985; Kramer, 1991). Physiological measures of mental workload also offer some advantages over alternative methods. Continuous data can be collected during task performance that may not interfere with primary task performance. In addition, obtaining these measures usually requires no additional effort from the individual. Disadvantages of physical measures include the necessity of potentially bulky equipment that may need to be attached to the individual, and an inability to isolate specific stages of information processing being required by the primary task because physiological changes do not always accompany alterations in mental processes or changes may be delayed. A selection of common physiological measures of mental workload is provided.

2.3.1.1. *Heart Rate Variability*

The reaction of the circulatory system to physical and mental workload has led to the consideration of heart rate and heart rate variability as indicators of workload (Meshkati, 1988). In one study, the cardiovascular reaction of individuals was monitored using the 24-hour Holter monitoring method that continuously recorded physiological changes occurring over a 24-hour period (Makowiec-Dabrowska, Bortkiewicz, Radwan-Włodarczyk, and Koszada-Włodarczyk, 1992). The study suggested that changes in

activities requiring differing levels of mental work, such as work, leisure time and sleep, could affect heart rate and the analysis of heart rate variation. Higher heart rate levels were associated with increased mental workload. From studies such as this, heart rate variability (HRV) is a physiological measure that is proposed as an indicator of mental workload.

Adequate systematic and comprehensive studies investigating the psychometric properties of HRV are absent (Nickel and Nachreiner, 2000). Past studies, including Miyake's (1997) review of physiological measures, indicate a low reliability of HRV parameters when the subject's respiration patterns are irregular. HRV is a relatively consistent and reliable measure of mental workload, however, when variations due to respiration are excluded. At higher levels of workload, interbeat interval tends to be more constant over time, whereas at lower workload levels the frequency fluctuates (Meshkati, 1988; Nickel and Nachreiner, 2000).

Effective measures of mental workload should be able to discriminate between mental load produced by different types of tasks (diagnosticity) and different levels of difficulty (sensitivity). HRV has been used in many situations to estimate levels of mental workload. The emotional and mental workload of blue- and white-collar workers was compared using HRV and subjective self-assessment (Myrtek, Fichtler, Strittmatter, and Brugner, 1999). Both methods showed no significant differences between the two groups. The activities performed by pilots and the corresponding mental workload has also been studied. HRV results differed depending on the activities being performed, with the largest changes occurring during landing and takeoff procedures and almost no alterations during acrobatic and gunnery training flight phases (Sekiguchi, Handa, Gotoh, Kurihara, Nagasawa, and Kuroda, 1978). Performance differences in HRV, however, may have been due to cardiovascular feedback during acceleration phases, particularly landing and takeoff procedures. HRV has been shown to be sensitive to different tasks, such as tracking tests, air traffic control situations, simulator flights, and actual flight conditions (Sekiguchi et al., 1978; Sirevaag, Kramer, Wickens, Reisweber, Strayer, and Grenell, 1993; Tattersall and Hockey, 1995). The findings of the research performed on flight engineer trainees support the use of HRV as a physiological index of mental effort (Tattersall and Hockey, 1995). HRV was found to be sensitive to different phases of the

work environment, with suppression occurring during mentally demanding problem-solving tasks. In addition, decreased HRV was used to indicate an increase in mental workload for train drivers while at higher rates of speed as compared to slower cruising speeds (Myrtek, Deutschmann-Janicke, Strohmaier, Zimmermann, Lawrenz, Brugner, and Muller, 1994). Sammer's (1998) work indicated that the analysis of heart dynamics could provide information regarding the complexity of the task being performed, whether it is mental, physical, or a combination of both.

2.3.1.2. *Blink Rate*

Eye blinks occur naturally, but blink rate is altered according to the task being performed. Assessing mental workload of pilots has been a major concern within flight research. Blink rate is used to investigate the demands of flying tasks (Hankins and Wilson, 1998; Wilson, Fullenkamp, and Davis, 1994). Evidence indicates that blink rate decreases with increased demands in the flight environment. This relationship between increased mental demands and eye blink rate has also been shown in other environments (Brookings, Wilson, and Swain, 1996; Stern and Dunham, 1990). As task difficulty increases, the interval between each blink becomes larger. This occurrence results in the decrease of blink rate over time (Veltman and Gaillard, 1998).

2.3.1.3. *Event-related Potential*

Event-related evoked potential (ERP) reflects the speed of neural events related to attention and short term memory. Evidence exists to support the use of ERP parameters as workload indices (e.g. Donchin, Kramer, and Wickens, 1986; Sirevaag et al., 1993; Ullsperger, Freude, and Erdmann, 2001). ERP parameters are sensitivity to allocation of processing resources. Components (e.g. N100, P300, P3) are elicited by primary and secondary tasks and indicate expenditure of perceptual and central processing resources (see Donchin, 1987; Fowler, 1994; Kok, 2000; Wickens, Kramer, Vanasse, and Donchin, 1983a). Application of ERP measures with dual task situations is particularly relevant for supporting the idea of capacity (Kahneman, 1973; Moray, 1967) and investigating resource allocation. Increases in mental workload have been associated with decreases in ERP measures (Hohnsbein, Falkenstein, and Hoormann, 1995; Kramer, Trejo, and Humphrey, 1995; Sirevaag et al., 1993).

2.3.2. Subjective Measures

In addition to perceptions of physical stimuli reviewed above, subjective measures of mental workload also provide useful workload assessment information. Subjective measures are based on an individual's assessment of the workload experienced (Reid and Nygren, 1988) and requires the individual to provide judgments of effort that are associated with performance of a task or combination of tasks (Eggemeier, Wilson, Kramer, and Damos, 1991). A number of rating scale techniques have been developed and shown to be sensitive to variations in demands imposed by different tasks. Several subjective techniques for assessing mental workload are: NASA Task Load Index, Subjective Workload Assessment Technique, Modified Cooper-Harper scale, Likert scales, Instantaneous Self Assessment, Bedford workload scale, Analytical hierarchy process, and Hart and Hauser rating scale (Mital and Govindaraju, 1999). Some of the more commonly used techniques are described more completely in the sections below.

2.3.2.1. *NASA Task Load Index (NASA-TLX)*

The NASA Task Load Index (NASA-TLX) provides an overall subjective workload score based on a weighted average of ratings on six subscales or dimensions: mental demands, physical demands, temporal (time) demands, own performance, effort, and frustration, as described by Hart and Staveland (1988). Each of the six scales is used to represent the underlying characteristics of subjective workload. At the conclusion of a task, subjects provide ratings on each of the six dimensions. Ratings from the scale are then weighted on the basis of data generated by the subject concerning the contributions of each dimension to the total workload associated with performance of a task. Rating scale definitions are provided in Table 1. The weighted ratings are then combined to create an overall index of subjective workload (Eggemeier et al., 1991). Although the physical demand of the task is included in the overall rating provided by the NASA-TLX, the index is not used as a measure of physical workload but instead recognizes the potential influence of physical activity on the perception of mental workload.

Table 1. NASA Task Load Index (NASA-TLX) rating scale definitions (from Hart and Staveland, 1988).

Title	Endpoints	Descriptions
Mental Demand	Low/High	How much mental and perceptual activity was required? Was the task easy or demanding, simple or complex, exacting or forgiving?
Physical Demand	Low/High	How much physical activity was required? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
Temporal Demand	Low/High	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
Performance	Good/Poor	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
Effort	Low/High	How hard did you have to work (mentally and physically) to accomplish your level of performance?
Frustration Level	Low/High	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Experimental results indicate that the NASA-TLX is a sensitive instrument for assessing subjective workload in a number of tasks (Damos, 1991; Hart and Staveland, 1988). It has also been shown to be applicable in a number of different task environments, such as flight simulation, actual flight tasks, air defense, remotely controlled vehicles and signal detection (Damos, 1991). Consistent scores are produced among people who are performing the same task, reducing between-rater variability (Vidulich and Tsang, 1986).

The NASA-TLX has been used to measure mental workload in a variety of circumstances. Examples include the effects of long duration vigilance tasks (Temple, Warm, Dember, Jones, LaGrange, and Matthews, 2000) and the effects of a prior task load on a subsequent subjective workload (Miyake, 1997). In addition, mental workload was measured while individuals performed mobile telephone tasks (Alm and Nilsson, 1995). Gender differences in mental workload during sustained attention tasks were also determined using the NASA-TLX. Males and females performed spatial and temporal tasks with gender differences in mental workload found in the performance of spatial tasks but not the temporal tasks. In addition, women tended to rate the overall workload

associated with the spatial task to be greater in comparison with men (Dittmar, Warm, Dember, and Ricks, 1993).

Extensive application in multi-task environments has been performed, including experiments within flight simulators, (Battiste and Bortolussi, 1988; Nataupsky and Abbott, 1987; Tsang and Johnson, 1989; Vidulich and Bortolussi, 1988) actual flight (Shively, Battiste, Matsumoto, Pepiton, Bortolussi, and Hart, 1987), air defense (Baird and Noma, 1978; Bittner, Byers, Hill, Zaklad, and Christ, 1989; Hill, Byers, Zaklad, and Christ, 1989; Hill, Zaklad, Bittner, Byers, and Christ, 1988) and remotely piloted vehicles (Byers, Bittner, Hill, Zaklad, and Christ, 1988). In each circumstance, the composite ratings of the NASA-TLX demonstrated the capability of individuals to distinguish levels of mental workload produced by varying levels of situational requirements. Pilots were able to distinguish the mental workload for different flight segments (Battiste and Bortolussi, 1988; Shively et al., 1987) and between low and high workload scenarios (Battiste and Bortolussi, 1988; Tsang and Johnson, 1989). Although the NASA-TLX ratings were able to distinguish differences associated with demand levels of various flight phases in Battiste and Bortolussi (1988), they failed to demonstrate a difference between separate control configurations (all-manual versus mixed manual/speech control) that were studied (Vidulich and Bortolussi, 1988).

Implementation of the NASA-TLX in flight environments indicates that the technique appears to be a viable approach for workload assessment in multi-task environments. The scale has shown a broad range of global sensitivity and may be capable as a diagnostic assessment technique (Damos, 1991). Vidulich and Bortolussi (1988) support the use of the individual sub-scales as diagnostic tools because the NASA-TLX is sensitive to separate changes in each of the dimensions. Mental workload changes, therefore, can be specified to one dimension measured by the NASA-TLX when task designs are altered.

2.3.2.2. *Subjective Workload Assessment Technique (SWAT)*

The Subjective Workload Assessment Technique (SWAT) requires subjects to rate the amount of workload perceived (low, medium, and high) on three dimensions that are assumed to constitute critical components of subjective workload: time load, mental

effort load, and stress load (Reid and Nygren, 1988; Reid, Shingledecker, and Eggemeier, 1981). The procedure includes two phases, scale development and event scoring (Reid and Nygren, 1988). During scale development, subjects provide the necessary weightings for combining workload ratings from the three dimensions (Reid and Nygren, 1988; Reid et al., 1981). In the second phase, subjects perform the task and rate the workload on the three dimensions. Each dimension has a unique descriptor for the low, medium, and high levels of workload as can be seen in Table 2 (Reid, Potter, and Bressler, 1989).

Table 2. Subjective Workload Assessment Technique (SWAT) rating scale descriptors for low, medium, and high levels (from Reid et al., 1989).

-
1. Time Load
 - a. Often have spare time. Interruptions or overlap among activities occur infrequently or not at all.
 - b. Occasionally have spare time. Interruptions or overlap among activities occur frequently.
 - c. Almost never have spare time. Interruptions or overlap among activities are very frequent, or occur all the time.

 2. Mental Effort Load
 - a. Very little conscious mental effort or concentration required. Activity is almost automatic, requiring little or no attention.
 - b. Moderate conscious mental effort or concentration required. Complexity of activity is moderately high due to uncertainty, unpredictability, or unfamiliarity. Considerable attention required.
 - c. Extensive mental effort and concentration are necessary. Very complex activity requiring total attention.

 3. Psychological Stress Load
 - a. Little confusion, risk, frustration, or anxiety exists and can be easily accommodated.
 - b. Moderate stress due to confusion, frustration, or anxiety noticeably adds to workload. Significant compensation is required to maintain adequate performance.
 - c. High to very intense stress due to confusion, frustration, or anxiety. High to extreme determination and self-control required.
-

Developing scales within the SWAT procedure requires application of a conjoint measurement technique. Subjects must define the relative weights and the composition rule that fits their perception of the workload being required (Reid and Nygren, 1988). A card sort procedure allows subjects to order the combinations of descriptors that represent their perception of the lowest workload situation (1, 1, 1) to the highest workload situation (3, 3, 3) and create a unique workload scale. Resulting workload scales are then used to score the tasks using event scoring. During event scoring, subjects perform the

desired task and rate the workload for each of the three dimensions on a three-point scale (Eggemeier et al., 1991).

The three dimensions in this scale were developed somewhat intuitively (Sheridan and Simpson, 1979). Boyd (1983) determined that the dimensions are not independent and that ratings tend to increase for all three dimensions even if only one dimension is altered. The dimensions are weighted based on the definition of workload being employed by the individual. The scaling algorithm produces interval-scaled estimates of the workload dimensions as well as estimates of their combined effects (Reid and Nygren, 1988). SWAT is unique among other workload rating scales because it demonstrates interval-scale properties (Reid and Nygren, 1988). Although results are similar to those obtained using the NASA-TLX, they are slightly less consistent across individuals (Hill, Iavecchia, Byers, Bittner Jr, Zaklad, and Christ, 1992; Vidulich and Tsang, 1986).

SWAT has been used to detect variations in mental workload during a variety of tasks, including visual display monitoring, memory, and manual control (Damos, 1991). It has also been applied in multi-task environments, including military flight scenarios and commercial air travel (Battiste and Bortolussi, 1988; Corwin, 1989; Nataupsky and Abbott, 1987). In addition, successful assessments of mental workload have been performed during mobile air defense maneuvers (Bittner et al., 1989) and remotely piloted vehicle systems (Byers et al., 1988).

SWAT has been shown to be sensitive within multi-task environments and single-task laboratory situations. Existing results suggest that the procedure represents a global sensitivity to workload, but possesses limitations as a diagnostic assessment tool (Damos, 1991).

2.3.2.3. *Modified Cooper-Harper Scale (MCH)*

The Cooper-Harper Scale was originally developed to evaluate mental workload during aircraft handling tasks. Modifications have provided a more direct assessment of operator workload during more generic situations (Damos, 1991). In its modified version, the scale can be used for perceptual, cognitive, and communication tasks (Wierwille and Casali, 1983). A decision tree and a uni-dimensional 10-point rating

scale that ranges from easy (1) to impossible (10) is the basis of the Modified Cooper-Harper (MCH) Scale.

Applications of the MCH scale have included a number of flight simulator experiments (Casali and Wierwille, 1983; Casali and Wierwille, 1984; Itoh, Hayashi, Tsukui, and Saito, 1989; Skipper, Rieger, and Wierwille, 1986; Wierwille, Rahimi, and Casali, 1985) and situations where pilot communication loads were varied (Casali and Wierwille, 1983). The MCH scale was able to discriminate between low and moderate or high communication loads. Other studies have investigated communication loads and reaffirmed the sensitivity of the scale (Skipper et al., 1986). In addition to communication loads, mental workload was measured during different hazard detection conditions (Casali and Wierwille, 1984). As with differing communication loads, ratings differed between low and high or moderate levels. Wierwille et al. (1985) varied the quantity and complexity of navigation dilemmas that had to be resolved by the pilots. The MCH scale was able to differentiate between low and medium levels of central processing demands. In an experiment determining duration estimation, the Cooper-Harper Scale was used to determine the subjective mental workload of individuals completing flight simulations (Zakay and Shub, 1998). In addition to using the MCH to investigate flight simulator workload, the scale has been used to evaluate adverse conditions during commercial airline flights. It was reported that the takeoff and landing portions of a flight elicited higher subjective mental workload levels compared to the cruise phase. Furthermore, normal flight segments received significantly lower ratings than portions with abnormal conditions (Itoh et al., 1989).

The applicability of the MCH scale extends to environments other than flight. Results of studies involving multi-task environments confirmed the sensitivity of the scale. These include studies involving remotely piloted vehicle system (Byers et al., 1988) and workload ratings of a generic air defense system (Bittner et al., 1989). The MCH scale appears to represent a globally sensitive measure as opposed to a diagnostic measure of mental workload (Damos, 1991).

2.3.2.4. *Instantaneous Self Assessment (ISA)*

Instantaneous self-assessment (ISA) is a technique that has been developed as a measure of workload, and provides immediate subjective ratings of work demands during performance of primary work tasks such as air traffic control. Workload assessment by the individual is provided at intervals throughout the task. Tattersall and Foord (1996) compared the results of ISA with those gathered from other established workload evaluation techniques. Subjective ratings of the ISA were compared to mean heart rate, heart rate variability, and error in the primary task of tracking. Results showed that the ISA was sensitive to the variations in task difficulty, as compared with levels indicated by the physiological measures, however, primary tracking performance decreased during periods where ISA responses were required. The results suggest that the effectiveness of the ISA technique is limited in comparison to less intrusive measures of mental workload (Tattersall and Foord, 1996).

2.3.3. Critical Interpretation

Limitations exist within current mental workload assessment techniques. No physiological measures have been proven to be accurate measures of mental workload, although heart rate variability and other measures have been used in conjunction with subjective measures. Using multiple measurements provides a more comprehensive estimate of mental workload. The major scaling techniques, SWAT, MCH and NASA-TLX, have demonstrated sensitivity to different levels of task demand, and each has exhibited similarities in reliability and validity between these scales. All scaling procedures for determining mental workload have been shown to exhibit global sensitivity (Damos, 1991).

2.4. Physical Workload Assessment

There are many factors to consider when quantifying the physical workload experienced by people while performing a task, each of which influences the energy output of the individual in some way. These factors include the nature of the work, training, motivation, and environmental factors (Astrand and Rodahl, 1986).

Objective (physiological) and subjective methods have been developed to determine the physical demands of work in terms of the physical effort necessary to

complete the task. Methods exist for quantifying physical workload by physiological methods. Subjective methods, when used in conjunction with physiological methods, often provide a more comprehensive understanding of the working conditions and the physical effort required (Wickens et al., 1998). Several physiological and subjective methods for assessment of physical workload are described in the following sections.

2.4.1. Physiological Measures

Extensive examination of work physiology has shown that the physical demands of work, in terms of energy requirements and physical effort, must be considered when determining physical workload. There are a number of measures that have been investigated within the literature, including oxygen consumption, respiratory rates, heart rate, blood lactate levels, minute ventilation, blood pressure, body temperature, electrocardiogram (ECG), electromyogram (EMG), skin impedance, muscle tension (strength), papillary dilation, and speech analysis (Mital and Goviadaraju, 1999). Other physiological parameters may be used, but these are some of the most common. Further discussion is provided for the most common and useful indicators during field and industrial tasks.

2.4.1.1. *Oxygen Consumption*

Oxygen consumption is measured as the amount of air expired per unit of time and is the difference between the fraction of oxygen in the expired air and that in the inspired air. The metabolic conversion that takes place within the body is represented by oxygen consumption (Astrand and Rodahl, 1986; Harrison, Brown, and Belyavin, 1982). A roughly linear relationship exists between absolute oxygen consumption and energy expenditure or dynamic workload (Louhevaara, 1995). Oxygen consumption measurements are beneficial when investigating dynamic work, but not a good estimator of workload for static tasks. This is due to the restricted blood flow caused by compression of the blood vessels by sustained muscle contractions during static tasks (Astrand and Rodahl, 1986; Harrison et al., 1982). Job evaluations can at times be assisted by determining minute ventilation or minute volume, which refers to the amount of air breathed out per minute (Kroemer, Kroemer, and Kroemer-Elbert, 1990). Minute ventilation is usually measured concurrently with oxygen consumption because it is more

sensitive to changes in stress and anaerobic situations (Delistraty, Greene, Carlberg, and Raver, 1991).

Oxygen consumption is commonly used as a means for assessing physical components of workload and an individual's work capacity. Fibiger et al. (1986) compared the job demands of four types of sawmill operators utilizing information obtained from analyzing oxygen consumption. Objective indicators of exertion, including oxygen consumption, were compared to predetermined acceptable physiological criteria and subjective assessments of effort during studies of acceptable weights of lift during grocery bag transfers (Fredericks, Fernandez, and Rodrigues, 1994) and manual handling tasks (Snook and Ciriello, 1991). Lopez Calbet et al. (1993) used oxygen consumption as a physiological indicator during experiments that measured seasonal salivary cortisol and testosterone changes, while Quesada et al. (2000) estimated the biomechanical and metabolic effects of varying backpack loading while marching by examining oxygen consumption levels. Oxygen consumption can also be used as an indicator of physical fitness or health status, as was done with a population following spinal cord injury (Stewart, Melton-Roger, Morrison, and Figoni, 2000).

2.4.1.2. Heart Rate

Heart rate has been shown to increase as physical workload and energy demands increase. This change reflects the increased demand by muscles for more oxygen and the disposal of waste products. During moderate work intensities, heart rate is linearly related to oxygen consumption (Astrand and Rodahl, 1986). Due to the simplicity of measurement, heart rate is often chosen in industrial settings to estimate energy expenditure and physical workload. During static efforts, however, muscles require a greater blood supply, thus increasing heart rate, whereas oxygen consumption may not significantly increase (Kroemer et al., 1994). Differences between these measures exhibit a distinction between local and global demands of the body. It should also be noted that heart rate may be less reliable than oxygen consumption as an indicator of workload, because it can be influenced by other factors, including emotional stress, nervousness, apprehension, caffeine, or working in a hot environment (Spurr, Prentice, Murgatroyd,

Goldberg, Reina, and Christman, 1988). Despite possible limitations, heart rate is often used to represent an individual's physiological reaction to physical demands.

Heart rate has been used to aid in health assessments by categorizing the fitness levels of individuals (Stewart 2000). Mihevic (1983) identified fit and unfit individuals by heart rate levels during varying physical workload intensities. Since absolute heart rate measures are dependent upon the individual, changes in heart rate or normalized values are needed for accurate assessments and comparisons between individuals. Evaluation of heart rate measures have been used to estimate physical intensity levels of a task (Johansson and Borg, 1993; Louhevaara, 1995) allowing for the differences in metabolic costs to be determined and the intensity of effort required to be regulated (Pandolf, Kamon, and Noble, 1978; Shephard, 1994).

Physiological measures, including heart rate, have also been proposed for determining safe working levels, particularly for manual materials handling. Zhang (1999/2000) studied the physiologic response to several lifting techniques, frequencies and distances. Changes in metabolic costs (e.g. heart rate) corresponded to various lifting characteristics and identified changes in lifting capacities. Heart rate levels are used extensively to maintain safe limits and permissible work loads, particularly during the determination of maximum acceptable weights of lift (Jorgensen, Davis, Kirking, Lewis, and Marras, 1999; Snook and Ciriello, 1991). Safe lifting limits based on heart rate were found to be more conservative (i.e. lower recommendations) as compared with psychophysical techniques (Garg, 1980). Straker (1997) used heart rate to objectively estimate the risks of manual handling tasks. It was determined that risks of combination tasks could not be estimated from risk assessments of the individual tasks.

Heart rate is commonly used as a primary indicator of physiological stress, exhibiting a fairly linear relationship with ratings of perceived exertions in healthy individuals (Borg, 1970). Heart rate alone was found to be moderately correlated, using regression analysis, with ratings of perceived exertion (Noble, Metz, Pandolf, and Cafarelli, 1973b). A combination of heart rate and blood lactate levels, however, substantially increased the accuracy of prediction during bicycle ergometer exercise (Borg, Ljunggren, and Ceci, 1985) and arm and leg exercise (Borg, Hassmen, and Lagerstrom, 1987).

Ratings of perceived exertion are not as sensitive to changes in workload as heart rate (Mihevic, 1983). Noble et al. (1973a) compared ratings of perceived exertion during walking and running and found that subjective ratings closely followed heart rate when metabolic differences between modes are substantial, particularly at low and high velocities. Statistical analyses were used to illustrate the incongruence, however, between the perceived exertion and metabolic intersection points. The relationship between heart rate and perceived exertion also differs for patients suffering from coronary or arterial disease. A given increase in heart rate corresponded to a greater increase in ratings of exertion in affected individuals as compared to healthy individuals (Borg and Linderholm, 1970).

2.4.1.3. Blood Lactate Levels

Physical performance of all but the briefest duration requires that oxygen be provided to the working muscles. Depending on the individual, there is some critical level where the oxygen-transporting system cannot provide sufficient oxygen to the muscles. If there is insufficient oxygen available anaerobic processes are increased, resulting in production and accumulation of lactic acid. Lactic acid buildup, and associated changes in pH, is believed to be primary causes of muscle fatigue and the resulting sensation of discomfort and pain (Kroemer et al., 1990).

Changes in blood lactate levels, similar to other physiological measures, have been compared to ratings of perceived exertions. Borg (1987; 1985) showed that the increases in perceived exertion and perceptions of aches or pains in the arms and legs corresponded to both increases in heart rate and blood lactate while individuals performed arm and leg ergometer work. It was argued that these results supported the idea that a combination of heart rate and blood lactate is a better predictor of perceived exertion and discomfort, than is each of the single physiological variables (Borg et al., 1985). Further work has used similar physiological measures to validate several category scales. Noble et al. (1983) showed a strong correlation between the Borg category-ratio scale (CR10) and blood lactate levels. Neely et al. (1992) compared the visual analogue scale (VAS) to the category-ratio scale (CR10) using physiological measures as guides of

physical exertion and determined that the CR10 scale could discriminate exertion intensities at high intensity levels.

2.4.1.4. *Blood Pressure*

Blood pressure refers to the pressure in the large arteries caused by cardiac contractions and subsequent cyclic blood flow. The large arteries offer relatively little resistance to blood flow and serve to absorb and distribute large pressure changes to help circulate the blood through the distal tissues. Maximal arterial pressure produced by contraction of the left ventricle is called systolic pressure, while the minimum pressure when the heart muscle is relaxed is called diastolic pressure (Kroemer et al., 1990). Blood pressure measurement usually interferes with most industrial tasks and is thus infrequently used for estimating physical workload. During work involving awkward static postures, however, blood pressure may be a more accurate index than other measurements, such as oxygen consumption and heart rate that have been shown to be less accurate (Lind and McNicol, 1967).

Borg et al. (1990) determined that perceived exertion during a range of exercise levels, determined by blood pressure, was not altered after moderate alcohol consumption. Monitoring of physiological measures, such as blood pressure, has been used to evaluate the effects of drugs, exercise, and physiologic stress on perceived exertion (Palombo, Marabotti, Genovesi-Ebert, Giaconi, Michelassi, Fommei, and Ghione, 1988). In addition, blood pressure is one measure that aids in determining the current health status of healthy individuals and those with some injuries or medical conditions (Stewart et al., 2000).

2.4.2. Subjective Measures

The psychophysical approach assumes that humans can sense and integrate the perception of strain on body functions and their capabilities. Subjective measurement techniques rely on an individual's ability to relate their sensations to some quantitative measure (Noble and Robertson, 1996). Stephen's Power Law provided a quantitative method for determining the relationship between physical stimuli and perception, and laid a foundation for a connection between physical stimuli and perception of effort (Noble and Robertson, 1996; Stevens, 1958; Stevens, 1975).

Subjective ratings are important complements to behavioral and physiological measurements of physical performance and work capacity. This is true for both theoretical analyses and applications. Modern scales and techniques include linear scales from 0 to 10, graded and category scales, questionnaires, pain estimation charts, visual analog scales, and several variations of methods for determining maximum acceptable weights.

2.4.2.1. Category Scales and Category-Ratio Scales

Category scales are equally partitioned continuous rating scales that designate categories with adjectives or a finite set of numbers (Noble and Robertson, 1996; Stevens, 1974). Therefore, uninterrupted categories are used to indicate steps along the continuum being scaled. Scales with ratio properties require individuals to estimate subjective intensities on a scale with an absolute zero and equivalent scale steps. This is in contrast to the interval scale, which has equal steps but no true zero (Borg, 1998). Category methods are valuable in applied situations when differences between individuals are depicted (Borg, 1982).

Scaling techniques vary in structure and complexity. For example, Armstrong et al. (1989) asked participants to rate their perceptions of grip force, tool mass and handle size on a continuous scale from 0 to 10. More complex versions of such a scale have been developed, with the most commonly used being that developed by Borg.

Early scales related physical responses to numeric scales, including the first version of the Borg Ratings of Perceived Exertion (RPE) Scale (Borg, 1970; Borg, 1978; Borg, Diamant, Strom, and Zotterman, 1967; Borg and Linderholm, 1970; Borg, 1973). Changes and adaptations of the early scales have led to the development of the Borg RPE Scale (modified to final form in the mid-80s) and the Borg CR10 Scale (Borg, 1985; Borg, 1998) that are illustrated in Figure 7 and Figure 8, respectively.

6	No exertion at all
7	
8	Extremely light
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

Figure 7. Borg Ratings of Perceived Exertion (RPE) Scale (adapted from Borg, 1970).

0	Nothing at all	“No P”
0.3		
0.5	Extremely weak	Just noticeable
1	Very weak	
1.5		
2	Weak	Light
2.5		
3	Moderate	
4		
5	Strong	Heavy
6		
7	Very strong	
8		
9		
10	Extremely strong	“Max P”
•	Absolute maximum	Highest possible

Figure 8. Borg Category Ratio (CR10) Scale with “P” representing perception (adapted from Borg, 1982).

The RPE scale (Figure 7) is a category scale that relates the intensity of an individual's perception to a perceptible range (Borg, 1985). Unlike previous development of rating scales, the RPE scale was constructed in relation to an objective physical measure, heart rate. It was developed based on subjective force estimates provided by subjects while performing short-time work on a bicycle ergometer, designed to create a stepwise increase in workload. Subjective values rose linearly with heart rate and physical workload determined by the power output on the bicycle ergometer (Borg, 1973). High correlation between RPE ratings and heart rate was substantiated in future studies (e.g. Borg, 1977; Borg and Ottoson, 1986; Pandolf, 1983).

Values for the RPE Scale range from 6 to 20, originally intended to indicate physical exertion levels corresponding to heart rates ranging from 60-200 beats per minute for healthy males. Values on the scale approximately matched a heart rate of ten times the value (e.g. a rating of 13 would correspond to 130 beats per minute). This relationship was not intended to be taken too literally, however, since heart rate depends upon many factors (Borg, 1982). The scale contains verbal anchors that allow individuals to choose a number that represents their feelings of exertion. Different versions of the scale contain slightly different terms, but all range from "very, very light" to "very, very hard" with some type of "moderate" term in the middle of the range (Borg, 1998; Borg, 1982). Original validity of the RPE Scale was determined by Skinner et al. (1973) using a bicycle ergometer and two separate protocols, a standard graded exercise test and randomized presentation of the same power output levels.

Borg also developed a category-ratio (CR10) scale (Borg, 1982). The purpose of this scale (Figure 8) was to adapt the RPE Scale and create an interval scale with ratio properties that was based on physiological measures having positively accelerating functions, as compared to the linear behavior of heart rate. It was kept simple by reducing the number of categories to 12, values ranging from 0 to 10, with "0" for "nothing at all" and 0.5 for "extremely weak (just noticeable)". Furthermore, the terms were changed from "light" and "hard" to "weak" and "strong". To prevent a ceiling affect, the term "maximal" was placed outside of the scale to be used at the subject's discretion (Borg, 1998; Noble and Robertson, 1996). The ceiling affect had been a concern with the RPE Scale and visual analog scales (Borg, 1998). The CR10 Scale has

also been correlated with physiological measures, such as heart rate, blood lactate, and muscle lactate, supporting the validity of the scale (Borg et al., 1987; Borg et al., 1985; Noble et al., 1983).

Extending the relationship between the CR10 Scale and physical work, Marks et al. (1983) used category-ratio estimates to identify individual differences in perceived exertion, which correlated with differences in heart rate. This research further confirmed Borg's model of perceived exertion and supported Borg's hypothesis that in dynamic work, maximal sensation is at least roughly equivalent across subjects.

Bicycle ergometry has not been the sole method of validating ratings of perceived exertions and their relationship to heart rate. Noble et al. (1973a) found that perceived exertion generally followed heart rate responses during walking and running, but muscular discomfort at high walking velocities was believed to cause inconsistencies at the intersection of the walking and running curves. A review of clinical applications by Noble (1982) included monitoring stress test levels, cardiac rehabilitation training intensities, perceptual recovery after exercise, and the perception of pace during physical activity, such as running. Edgren et al. (1976) used the RPE Scale in the comparison of the validity of four physical work and performance tests on bicycle ergometers as indicators of cardiovascular fitness.

Perceived exertions have been used in several contexts to determine the physical effort required to complete tasks. In a package delivery industry, perceived exertions were used to estimate the amounts of load that correspond to various levels of load heaviness (Genaidy, Karwowski, Christensen, Vogiatzis, Deraiseh, and Prins, 1998). Truck drivers rated physical exertions required during heavy operations using the Borg CR10 Scale (Johansson and Borg, 1993). Psychophysical assessments have been used to investigate the perceived physical effects of resident-transferring methods on nursing assistants, identifying which methods minimize psychophysical stress (Zhuang, Stobbe, Collins, Hsiao, and Hobbs, 2000).

In general, ratings of perceived exertions can be used to determine appropriate design parameters (e.g. efficient working postures, task frequency, work capacity, tool assessment) since a strong correlation exists between subjective values and objective measures of physical exertion. Although metabolic differences during work are

important contributors in determining ratings of perceived exertion, local feelings of strain in the working muscles and joints have been shown to dominate the perception of exertion to the extent that metabolically dissimilar levels of exertion can be perceived to be equally demanding (Pandolf et al., 1978). This must be considered when using either the Borg RPE Scale or the Borg CR10 Scale to estimate the physical workload of a task.

Questions regarding the efficacy of the Borg RPE Scale have arisen while monitoring subjective estimates of exercise intensity in progressive (or graded) exercise tests. During treadmill exercise protocols over a period of multiple days, subjective RPE ratings varied as much as three units during repeated testing sessions (Lamb, Eston, and Corns, 1999). These findings cast uncertainty on the test-retest reliability of the RPE Scale. Additional research is required to corroborate these findings and identify possible ramifications. Reliability should be tested for other types of exercise and the effects of multiple exposures (or habituation) to the scale assessed. Borg (1998) asserts that the CR10 is reliable, with measurement errors of approximately 6%. This assertion was based on correlation coefficients of approximately 0.79 and retest correlations of 0.98 (Neely 1992).

Other scales have been developed to determine perceived exertion. Fleishman et al. (1984) created a 7-graded scale based on values from 1 to 7 converted from the Borg's 15-graded RPE scale. The seven anchors were identical to Borg's Scale, with the numerical intervals reduced by half and beginning with "1" instead of "6". The ratings were based on 37 occupational and 62 recreational tasks whose metabolic costs had been previously determined. Personnel experts rated each task to determine the required physical effort (Fleishman et al., 1984). The expert ratings were highly correlated to the actual metabolic costs of the activity, indicating a strong relationship between perceptions of effort and actual effort required to complete the task. Furthermore, this study supports the idea that different individuals perceive equivalent effort for task performance. Similarities in ratings of perceived exertion suggest that group ratings of perceived effort can be used to accurately reflect metabolic costs of task performance (Fleishman et al., 1984), as opposed to individual ratings that only represent the effort perceived by one person and are not always an accurate representation of the population's perception.

Visual Analog (VA) Scales are commonly used to estimate exertion, pain and discomfort (Huskisson, 1983). These scales consist of a line, often 10 cm long, with anchored endpoints often denoted by “minimal” and “maximal”. An example of a VA Scale is shown in Figure 9. Individuals are instructed to indicate the magnitude of their perception by marking the scale appropriately (Price, 1994). VA scales are useful for determining individual differences. Responses provided using a VA scale highly correlate with Borg CR10 ratings (Prince, 1994; Borg, 1998).

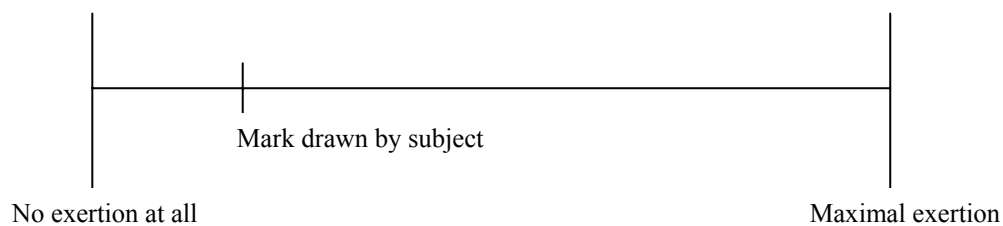


Figure 9. Visual analog scale example, to assess perceived levels of exertion.

VA Scales have been used in a variety of situations and working environments. A comparison of a visual analog scales and the CR10 Scale was performed with individuals asked to drill screws into a metal sheet at varying locations (Ulin, Ways, Armstrong, and Snook, 1990). Perceived exertions were recorded using both scales. Although the scales were comparable in sensitivity and use, the subjects preferred the Borg scale because it contained many verbal anchors. In a similar experiment, perceptual ratings given on a VA Scale and the CR10 Scale were compared while subjects performed an exercise test using a bicycle ergometer (Neely et al., 1992). Blood lactate levels and heart rate were used as correlates to sensory perception. It was shown that although VA Scales are reliable, the CR10 scale has a greater ability to discriminate differences in perception at high intensity levels.

Different scales and techniques can be combined to provide more information than each tool individually. A pain assessment instrument including a questionnaire, visual analog scale and pain drawings were used in combination to evaluate subjective

perceptions of pain in the neck, shoulders and thoracic spine (Bjorksten, Boquist, Talback, and Edling, 1999). The set of ratings were compared with clinical diagnoses, which established the validity of the subjective reports of the respondents. The study supported the use of such a multimodal pain assessment instrument to reveal conditions in the neck and shoulders and thoracic spine, common sites of work related musculoskeletal disorders. Similar methodologies have been applied in other settings, such as for manual materials handling tasks (Krawczyk, 1996; Kumar, Narayan, and Bjornsdottir, 1999). The absolute and relative sensitivity of Borg's RPE Scale, a visual analog scale, and body part discomfort ratings were determined during varied manual materials tasks (Kumar et al., 1999). The RPE Scale was able to discriminate between all conditions studied, whereas the VA Scale could only differentiate between the symmetries and headrooms investigated. Finally, the body part discomfort ratings were not sensitive to any of the task conditions. Based on the results of the study, it appears that appropriate and reliable information can be obtained from psychophysical tools if a match is found between task demands and the basis of the psychophysical procedure being implemented.

2.4.2.2. *Maximum Acceptable Weight of Lift*

Psychophysics and category scales have been applied to many areas of investigation. These include, but are not limited to, human audition, olfactory perception, exercise science, psychology and ergonomics. Applications within industrial ergonomics have included the psychophysical method of adjustment for manual materials handling (lifting, lowering, pushing, pulling, carrying, and walking) and associated maximum acceptable weights of lift (MAWLs), where the latter are amounts that a person deems appropriate to lift for a given time period (Mital, 1983a). The main feature of this method is that the observer is given an opportunity to control the changes in the stimulus that are necessary to achieve the desired threshold. The method of adjustment generally involves setting the initial stimulus intensity (e.g. weight) significantly below or above the expected threshold, and then allowing the observer to either increase or decrease the intensity level until it is just perceptibly too high or too low (Gescheider, 1985).

A main focus of MAWL research is to determine lifting capacities based on a person's subjective perception of exertion. A central assumption implicit in using MAWLs is that workers are able to determine with some accuracy the highest acceptable workload that can be maintained for a given period of time (Karwowski, 1991). The individual must thus be able to rate the perceived effort in a lifting task and produce an individually acceptable level of performance on this task. An additional criteria is that the self-chosen level of performance is also safe, or likely to minimize manual handling injuries (Karwowski, 1996). Research to date has not confirmed that these assumptions are true when the method is implemented. It should be noted that the standardized instructions typically used do not explicitly refer to the worker's safety (Garg, 1980; Karwowski, 1996). In addition, more study is needed to quantify the specific relationships between subjective perception of load heaviness and the lifting norms derived based on the psychophysical methodology.

Benefits of this psychophysical method include its simplicity and ease of determination. MAWL research can be performed in most organizations because no special equipment is needed. Although the entire process can be time consuming, this procedure is more time efficient than observing workers for an entire workday. An advantage is that investigation of dynamic trials is possible and relatively straightforward (e.g. in contrast to biomechanical studies).

Numerous prior studies have examined MAWLs in a variety of different situations. Databases of MAWLs are continually being updated to provide guidelines for designers and industrial engineers. The first tables of MAWL values were created by Snook and colleagues at Liberty Mutual Insurance (Ciriello, Snook, and Hughes, 1993; Mital, 1992; Mital, Foononi-Fard, and Brown, 1994; Snook, 1978; Snook and Ciriello, 1991; Snook and Irvine, 1967). Additional investigations have determined what and whether different criteria affect self selected limits (Asfour, Ayoub, and Genaidy, 1984; Ciriello et al., 1993; Davis, Jorgensen, and Marras, 2000; Garg, 1980; Gibbons, Videman, and Battie, 1997; Jorgensen et al., 1999; Mital, 1992; Mital et al., 1994; Putz-Anderson and Grant, 1994; Snook, 1978; Snook and Ciriello, 1991). Several measures have been found to be important, such as symmetry, lifting frequency, height of lift, task duration, load size and the presence or absence of couplings, and have subsequently been used to

model and predict maximum acceptable limits (Chen, Aghazadeh, and Lee, 1992; Genaidy, Asfour, Mital, and Waly, 1990; Jiang and Ayoub, 1987; Jiang, Smith, and Ayoub, 1986; Lee and Chen, 1996a; Lee and Chen, 1996b). Karwowski et al. (1992) suggests that there are limits to individual levels of load discrimination, with minimum differences in weight of at least 12% required between loads, suggesting that previous MAWL experiments may need to be reexamined. An emphasis on safe limits, as opposed to acceptable limits, was also found to lower psychophysical design limits for manual lifting tasks (Karwowski, 1996).

In a recent review of the classical psychophysical approach for determining load acceptability, Karwowski et al. (1999) suggested that a new approach to manual lifting tasks based on cognitive engineering is needed to improve the quality of research methodologies currently used in this field. In addition, Ayoub and Dempsey (1999) presented the advantages and disadvantages of the psychophysical approach as applied to manual materials handling. Advantages include the realistic simulation of industrial work, ability to study intermittent tasks, reproducibility of results, specificity of results, low cost, and minimal time commitments. Disadvantages consist of the assumption that subjective workloads are correlated with injury level criteria, lack of objectivity in results, and lack of sensitivity to bending and twisting while performing manual handling tasks.

Over 100 studies have examined particular aspects of lifting and other types of manual handling, and the influence of several task characteristics such as asymmetric lifting, squat versus semi-squat techniques, frequency of lift, lifting combinations, repetitive lifting, side lifting, back lifting, prolonged lifting, horizontal lifting, task duration, and differing postures (Capodaglio, Capodaglio, and Bazzini, 1995; Ciriello, Snook, Blick, and Wilkinson, 1990; Fredericks et al., 1994; Gallagher, 1991; Gamberale, 1988; Garg and Badger, 1986; Lee, Waikar, and Aghazadeh, 1990; Ljunberg, Gamberale, and Kilbom, 1982; Morrissey and Liou, 1988; Straker and Cain, 1999/2000; Wu, 1999). Other work has examined the effects of varied instructions provided to the individual (Rice, Murphy, Sharp, Mello, and Bills, 1998) or compared results from contrasting subject groups, such as experienced versus inexperienced materials handlers (Mital, 1987). The instructions and design of the experiment can greatly alter the estimated

limits. Mital (1983) used a 25-min period of adjustment and lifting to estimate appropriate load levels for an eight-hour workday, however, subjects tended to overestimate their capabilities. Psychophysically based limits have also been related, though poorly, to static strength or isokinetic lifting strength (Garg and Beller, 1994). Although this approach continues to be refined and validated, it is widely used in industrial settings.

2.4.2.3. *Questionnaires and Pain Estimation Charts*

Individuals are able to provide a wealth of information regarding their perceptions and preferences. Pain and/or discomfort that accompany performance are often a critical type of such information, and must be eliminated or at least minimized to facilitate an effective and efficient system. One procedure for determining potentially painful or uncomfortable situations is to ask the individual about their physical reactions to the tasks that they perform. Determining this is accomplished by using qualitative self-reports or questionnaires and pain estimation charts.

Self-reports can be used as diagnostic tools and as a proactive surveillance instrument. As an example, self-reports of perceived discomfort were collected from 797 employees of a public utility company using a body map (Marley and Kumar, 1996). Ratings of frequency and discomfort for various body regions were used to identify which individuals had sought treatment for their work-related discomfort. Self-reports were shown to aid in early identification of ergonomic concerns and to help prioritize jobs for intervention. Other self-report techniques have been used to describe the distribution of bodily discomfort, and discomfort changes during a work period. Overall discomfort and discomfort of specified bodily regions were indicated on a 7-point scale for a group of spot welders in one study (Corlett and Bishop, 1976). Subsequent analysis revealed specific areas of inadequate man-machine compatibility and also permitted an evaluation of the effectiveness of machine designs (Corlett and Bishop, 1976). When self-reporting techniques are used in conjunction with measures of production performance, it is possible to identify areas where ergonomic changes are needed and the potential benefits obtained after an ergonomics intervention.

Subjective methods were used to detect small differences in backpack design because physiological and biomechanical comparisons were ineffective at discriminating this difference (Legg, Perko, and Campbell, 1997). Two subjective perceptual methods were used, category ratio scale (CRS) ratings of perceived discomfort and written questionnaires for comparing two types of leisure backpacks. The questionnaire was found to be more useful than the CRS for determining which backpack was preferred, providing adequate information about discomfort and individual preferences not directly related to comfort. Questionnaires have also been used to determine the physical workload imposed during low stress tasks such as monitoring video display units. One study was able to show that the location of the mouse on the table and the duration of mouse use seem to be risk factors for upper-limb injuries and discomfort (Karlqvist and Wenemark, 1996). Self-reports were also used to identify the duration of different work tasks, when utilizing a keyboard and mouse, and also the locations of the keyboard and the mouse on the working table. The authors found that self-reports of location had good intermethod reliability when compared with direct measurements.

Alternative methods of self-reporting have been implemented in many working environments. During one study, in addition to completing questionnaires, employees were required to maintain logbooks as self-assessments of the physical workload associated with the tasks they performed (Viikari-Juntura, Rauas, Martikainen, Kuosma, Riihimaki, Takala, and Saarenmaa, 1996). Task analyses and observations were compared with the answers to both the questionnaires and the logbook entries to assess the validity of self-reported physical workload. The accuracy of the self-assessment questionnaires was not high enough for studying quantitative risks of injury based on exposure levels. The logbook provided additional information but the perception of musculoskeletal pain was believed to have biased observations. Further research examined current and retrospective physical and psychological workload in men with varying degrees of low back pain (Hultman, Nordin, and Saraste, 1995). The methods used were a self-administered questionnaire (Nordic Occupational Classification), a rating scale of perceived exertion (CR10 Scale), and blind expert assessment built on a classification of job titles. Results indicated that more attention should be given to the

individual's perception of physical workload because the ratings provided corresponded with the blind expert assessment, indicating the validity of self-assessments.

An example of a self-assessment tool is the Nordic Questionnaire, which is an enhancement of generic body diagrams used for identifying painful regions of the body. This questionnaire, which includes body sketches for identifying painful regions of the body, has been standardized and is often used as an inquiry tool. The questionnaire format is clearly structured and requires binary or multiple-choice answers to indicate general and specific information regarding pain in various regions of the body (Dickinson, Campion, Foster, Newman, O'Rourke, and Thomas, 1992; Kuorinka, Jonsson, Kilbom, Vinterberg, Biering-Sorensen, Andersson, and Jorgensen, 1987). The McGill Pain Questionnaire is also used to provide subjective pain estimates by posing several questions regarding the location and type of pain being experienced (Melzack, 1975). Three measures are used to determine quantitative levels of clinical pain: (1) the pain rating scale, (2) the number of words chosen, and (3) the present pain intensity. The questionnaire was determined to be adequately sensitive to the detection of differences among pain relief methods.

A comparison of three psychophysical techniques for physical stress determination (Borg's RPE Scale, the Visual analog (VA) Scale, and the Body Part Discomfort Rating (BPDR)) was performed during several manual materials handling tasks (Kumar, Narayan, and Bjornsdottir, 1999). The RPE and VA Scales were most sensitive to changes in the lifting tasks, which were of a short duration, continuous and not biomechanically demanding. The BDPR, emphasizing discomfort and pain in specific regions of the body, was unable to differentiate between task variables. Results indicate that sensitivity of psychophysical tools is optimized when applied to appropriate situations, since subjective scores are based on the individual's assessment of various central and peripheral factors that change with task demands. For example, although the BDPR was not sensitive in the study by Kumar (1999), a pain assessment instrument based on three subjective self-assessment tools (a questionnaire on musculoskeletal pain, ratings on a visual analog scale, and pain drawings) was able to predict conditions in the neck, shoulders and thoracic spine when compared to clinical diagnoses (Bjorksten et al., 1999).

2.4.3. Critical Interpretation

Assessing workload levels involves many components. Substantial research in physical workload assessment has focused on the efficacy of Borg's RPE and CR10 Scales. Graded scales have advantages for assessment purposes in applied settings, while ratio-scaling procedures are more appropriate for evaluating changes in subjective sensations with alterations in stimulus intensity. Additional work, however, has examined the idea of a two-factor model incorporating both local and central parameters (Mihevic, 1981). The primary, or local factor, is the strain felt within the muscles, while the secondary, or central factor, is provided by input from the cardiovascular and circulatory system. The model implies that perception of effort is determined primarily from local factors, with secondary input provided by central factors.

Although other procedures exist, primarily other types of scales, the two Borg scales are the predominant techniques used to subjectively evaluate physical workload. Reasonable justification of these scales has been demonstrated by correlating subjective ratings with physiological measures (primarily heart rate). There has been no research, however, to support the use of these scales when substantial mental activity is required in addition to the physical workload that is being assessed.

2.5. **Joint Assessment of Physical and Mental Workload**

Specific techniques for assessment of physical workload and for assessment of mental workload have been widely investigated. In contrast, measurement of general workload, associated with tasks that incorporate both physical and mental dimensions, has received less attention. The lack of assessment tools for measuring combined physical and mental workload can partially be attributed to inconclusive research explaining the relationship between physical workload and its effect on cognitive performance. In addition, the combined effect of concurrent physical and mental demands has not been fully investigated. One reason for the relative lack of information may be the deficiency of current models explaining the relationship between attention and performance (National Research Council, 1997). Efficient performance requires concentration on task-related information and suppression of extraneous stimuli in order to avoid an information overload situation. Individual differences in response to physical

and mental demands compound the difficulty in understanding and measuring workload levels.

Nearly all existing methods have been developed in separate domains. One notable exception is the work of Mital and Goviadaraju (1999), which proposed that levels of myocardial oxygen consumption could potentially estimate both physical and mental components of workload. Myocardial oxygen consumption (MV_{O_2}) is a measure that is estimated empirically as a function of heart rate and systolic blood pressure (Equation 1).

$$MV_{O_2} = 0.14(\text{Heart Rate} \times \text{Systolic Blood Pressure} \times 10^{-3}) - 6.3 \quad (1)$$

A rise in physical and/or mental workload levels has been shown to increase heart rate, blood pressure, and myocardial contractility, which in turn increases myocardial oxygen consumption (Mital and Goviadaraju, 1999). Further research is necessary, however, to determine the proportion of myocardial oxygen consumption resulting from physical workload as compared to mental workload, and the sensitivity of the measurement.

Although there is limited research regarding collective measurement of combined physical and mental workload, there has been substantial study on the effects of physical activity on cognitive performance. Typically, individuals perform strenuous exercise tasks, usually on a bicycle ergometer or treadmill. Concurrently, or immediately following the exercise, subjects perform cognitive tasks, such as arithmetic or line matching. In the early 1970s, Davey (1973) and Gupta et al. (1974) showed that cognitive performance increased immediately following low levels of physical activity, but long term exercise caused decrements in mental performance, specifically tasks requiring short term memory. Five minutes of a step-up exercise may be sufficient to cause increased mental work and decrease performance (Gupta et al., 1974).

All results regarding the effects of physical activity on cognitive demands have not been uniform. McGlynn et al. (1977) found that concomitant exercise by males on a treadmill resulted in an increased speed of mental performance but had no significant effect on accuracy during a line matching task. Furthermore, the speed of response dropped dramatically at the termination of the exercise (McGlynn et al., 1977).

Continued research by McGlynn et al. (1979) on females, however, concluded that the same line matching task and exercise situation caused no effect on accuracy or speed, except in the last stage of the experiment. Similar to the males, the speed exhibited in the post-test was greater than the first three stages but not the fourth (McGlynn et al., 1979). McGlynn et al. (1979) believed that more research needed to be performed on males and females combined to formulate conclusive decisions. Hogervorst et al. (1996) also found increased speed during psychomotor and cognitive tests after subjects performed bicycle ergometer endurance trials. Furthermore, errors in cognitive performance did not increase (Hogervorst et al., 1996).

Other studies investigating the relation between exercise and cognitive performance have failed to support these results. Zervas (1990) found that completion of a combination of strenuous physical exercise had no effect on the performance of verbal, visuospatial, and numeric tasks. Increments in physical workload, while on a bicycle ergometer, were shown to improve performance on decision tasks yet impair performance on perception tasks (Paas and Adam, 1991). Decrements in physical workload resulted in opposite outcomes. Sparrow and Wright (1993), however, found no differences between control and exercise groups when different types of cognitive pre- and post-tests were administered.

Cognitive performance of fit and unfit individuals during and after exercise have been compared. While work in this area has not been definitive, Sjoberg (1980) claimed that fit subjects performed better than those that were classified as unfit, and hypothesized that this resulted from fit individuals ability to recover faster after exercising and thereby resisting the negative effects of exercise. Contradictory evidence was provided by Tomporowski et al. (1987), where fit and unfit individuals performing a treadmill test to voluntary exhaustion showed no differences in a free-recall memory task administered immediately following physical exertion.

Further clarification regarding the possible interactive effects of physical and mental workload, particularly during situations involving concurrent physical and mental demands, is needed to develop more comprehensive objective and subjective assessment tools. Although the effects of physical demands on mental performance have been studied, it is unclear as to the effect on subjective assessment of mental workload. The

effects of mental demands on physical performance have received less attention, with little regard given to subjective assessment of the physical workload. While subjective assessment measures have been extensively used in a single domain (e.g. mental or physical), there has been little research on the validity of current subjective assessment tools during situations that require concurrent physical and mental effort.

2.6. Postural Stability Assessment

The ability to maintain balance and postural stability during upright postures is a critical factor for successful task performance and minimization of loss of balance or falls. Falls from heights are a significant cause of fatalities among the American workforce. Loss of balance is a central mechanism believed to be responsible for many of these incidents. Although stable control of posture and balance is automatic for healthy subjects, it is oftentimes a challenging goal for individuals lacking balance stability due to fatigue, pathology, injury or age (Ferdjallah, Harris, Smith, and Wertsch, 2002). Improved fall prevention is necessary to move towards a reduction of fatalities and injuries related to falls; with control of postural stability being an integral component (Bagchee, Bhattacharya, Succop, and Emerich, 1998).

As highlighted by NIOSH (2000), falls from heights are a concern among multiple divisions of industry. Workers in many occupational settings are exposed to fall hazards on a daily basis. Using the National Traumatic Occupational Fatalities (NTOF) surveillance system, NIOSH (2000) determined falls from elevations to be the fourth leading cause of occupational fatality in the United States between 1980 and 1994. In the period from 1980 to 1994, 10% of all occupational fatalities occurred from falls. The NTOF system is based on information gathered on death certificates; therefore, these statistics are likely underestimates of the actual values due to the limitations of ascertaining appropriate and complete data from death certificates (National Institute for Occupational Safety and Health (NIOSH), 2000). Despite these limitations, approximately 80% of work-related fatalities are identified on death certificates (Stout and Bell, 1991).

Falls are initiated or caused by numerous factors. Decreased coordination between postural reflexes and voluntary movement has been shown to contribute to the

frequency of falling occurrences (Stelmach, Phillips, DiFabio, and Teasdale, 1989). Extensive studies have investigated the role of balance as a predictor of an individual's tendency to fall, particularly for the elderly and individuals with vestibular or proprioceptive deficits. Postural instability has been cited as an effective predictor of falls (Kellogg International Work Group, 1987). In a recent review, Hsiao and Simeonov (2001) suggested that the majority of occupational falls are a result of loss of balance. The basis for this conclusion comes from reports that indicate slips, trips, and imbalance as the most commonly mentioned reasons for loss of balance. Pan et al. (2000) provides an applied example in the context of a simulated construction task (drywall lifting and hanging during installation). Postural sway variables and instability indices derived from force plate measures were used to infer workers' tendency to fall due to a loss of balance.

Uncontrollable movement of the body contributes to the loss of balance. Fixed postures are not maintainable, however, since purely constant forces cannot be generated by the skeletal musculature. This includes upright stances, which create inherently unstable systems (Danis, Krebs, Gill-Body, and Sahrman, 1998). Equilibrium of the body is, therefore, achieved by constant repositioning of the body (Hunter and Hoffman, 2001).

Postural stability is defined as the ability to maintain and control the body center of mass (COM) within the base of support to prevent falls and complete desired movements (Ferdjallah et al., 2002). The COM is a point equivalent to the total body mass in the global reference system and is the weighted average of the COM of each body segment in 3D space. The vertical projection of the COM onto the ground is often called the center of gravity (COG). Both the COG amplitude and velocity of displacement must be controlled to remain standing (Danis et al., 1998). Postural sway is a measure of static balance where a person maintains his/her COG over his/her base of support by swaying, usually around the ankle joint axis (Horak, 1997).

Balance control is known to be a complex motor skill that involves the integration of sensory information and the planning and execution of flexible movement patterns (Ferdjallah et al., 2002). It is a perceptual-motor process that includes: (1) sensation of position and motion from the visual, somatosensory, and vestibular systems, (2) processing of that sensory information to determine orientation and movement, and (3)

selection of motor responses that maintains or brings the body into equilibrium (Schmidt, 1975; Schumann, Redfern, Furman, El-Jaroudi, and Chaparro, 1995).

Three major sensory systems are involved in maintaining balance and posture by contributing input from the individual and their environment: visual, vestibular, and somatosensory (Mirka and Black, 1990; Winter, 1995). Vision is the system primarily involved in planning our locomotion and in avoiding obstacles. Visual input is derived from sway-dependent motions of the head relative to the visual surroundings. Linear and angular accelerations are sensed by the vestibular system. Vestibular input is derived from head motions related to active or passive body sway in reference to gravity. The somatosensory system is composed of a multitude of sensors that discern the position and velocity of all body segments, their contact (impact) with external objects (including the ground), and the orientation of gravity (Mirka and Black, 1990; Winter, 1995).

Integration of information from the three sensory systems provides the individual with information about their orientation in space to allow for compensatory reflexive movements in order to maintain balance and postural control (Cobb, 1999). Sensory inputs are not solely responsible for maintaining postural control. It also depends on the integrity of the musculature, effectiveness of processing within the central nervous system, and intact neural pathways for motor control (Horak, Shupert, and Mirka, 1989).

Balance assessments evaluate how strategies change with alterations in support and sensory conditions, changes in an individual's expectation and experience and with changes in task constraints (Horak, Frank, and Nutt, 1996; Horak, Frank, Shupert, Stephens, Nutt, and Burleigh, 1992). The visual, proprioceptive, and vestibular systems are critical sources of afferent information that influence the control of stability (Danis et al., 1998). The importance of each system has been well established through observations of individuals deprived of sensory input from one or more of the three systems (Nashner and Peters, 1990). Alterations of each modality have been shown to impact balance and postural stability. In such situations, an overall lack of input, or lack of accurate input, generally decreases a person's postural control (Hunter and Hoffman, 2001; Mirka and Black, 1990).

Postural stability is most often characterized by measures based on the displacement of the center of pressure (COP). The COP is the point location of the

vertical ground reaction force vector. It represents a weighted average of all the pressures over the surface of the area in contact with the ground (Winter, 1995). The COP reflects the orientations of the body segments (joint angles), as well as the movements of the body (joint angular velocities and accelerations) to keep the COG over the base of support (Winter, 1990).

The vast majority of research on postural sway during quiet standing has analyzed time-varying locations of the COP from a single force platform (Winter, 1995). Thus, the COP signal can be used as an indirect measure of body sway (Ferdjallah, Harris, and Wertsch, 1999). Specifically, displacement of the COP on a platform has been measured and used as an index of postural stability in standing (e.g. Haas, Diener, Raap, and Dichgans, 1989; Nakamura, Tsuchida, and Mano, 2001; Nussbaum, 2003). The COP in both anterior-posterior (AP) and medial-lateral (ML) planes has proven to be a useful metric since substantial variability in both directions has been shown to exist during several experimental conditions (Harris, Riedel, Matesi, and Smith, 1993; Hunter and Hoffman, 2001; Winter, 1995). The planar trajectory of the COP over the test interval is commonly referred to as a stabilogram (Winter, 1990). Stabilograms provide various COP measures that have been used to derive several useful statistics, including sway length, sway area, velocities, path length, etc. (Ferdjallah et al., 1999; Winter, 1995).

To some extent, COP measures are not true estimates of body segment configurations since they are confounded by whole-body dynamics. Most researchers, however, have interpreted COP sway measures derived from force plates as valid indices of balance and postural stability, particularly when the task involves quiet standing or minor dynamic components (LeClair and Riach, 1996). This interpretation is supported by research that elderly fallers have a greater sway area as compared to non-fallers and that postural sway is sensitive to several manipulations of experimental conditions (Lichtenstein, Shields, Shiavi, and Buger, 1988; Lichtenstein, Shields, Shiavi, and Buger, 1989).

2.6.1. Cognitive Effects on Postural Stability

Recent research using a dual task paradigm suggests that sensorimotor processing, essential to postural control, requires attentional resources. Several researchers have

documented that even highly practiced postural tasks require some cognitive processing, and that the degree of processing varies with the complexity of the postural task (Brown, Shumway-Cook, and Woollacott, 1999). Allocation of attention during the performance of concurrent tasks is complex, depending on many factors including the nature of both the mental and postural task, the goal of the individual and instructions provided (Dault, Frank, and Allard, 2001a).

Attention-demanding secondary tasks compete with the postural control system for neural resources. Maki and McIlroy (1996) explored the influence of attention and distraction on physiological arousal and subsequently the control of postural sway. Although four differing secondary tasks were investigated, the mathematics task (counting backwards by 7's from 1000) was the only one found to significantly increase physiological arousal, which then caused changes in posture (forward leaning) and increases in leg muscle activation. This research suggests that a state of heightened physiological arousal, caused by cognitive demands, may lead to changes in posture and alter the effectiveness of subsequent stabilizing responses, ultimately increasing postural sway.

Dault et al. (2001b) explored the effects of a cognitive task (three versions of the Stroop task) on postural stability during three different standing conditions. Stroop tasks require the individual to report the color of a series of stimuli as rapidly as possible (Stroop, 1935). A typical condition used in ensuing studies (e.g. Hintzman, Carre, Eskridge, Ownes, Shaff, and Sparks, 1972; Keele, 1972) consists of color names that do not match the color of ink in which they are printed (e.g. the word blue printed in green). Minimal changes in COP displacement and velocity were provoked during a simple shoulder-width stance. This is a well-learned position that may have required only a minimal amount of attention, thus explaining the reduced effects on postural stability. When seesaws were added to the shoulder-width stance, the addition of the cognitive task resulted in an increased stiffness, indirectly shown by an increase in COP frequency and a decrease in COP amplitude. Adaptations of normal strategies were used to achieve a more critical stabilization of posture. When the seesaws were combined with a tandem stance (heel-to-toe), the addition of the cognitive task resulted in decreased postural stability in the frontal plane, manifested as an increase in COP frequency and COP

velocity. It can be inferred from these findings that the difficulty and novelty of a postural stance has an influence on postural stability, particularly when maintained during the performance of a cognitive task (Dault et al., 2001b).

Additional research by Dault et al. (2001a) required individuals to perform different working memory tasks during different postural stances. Cognitive tasks were based on Baddeley's working memory model: a verbal task, a visuo-spatial task with two levels of difficulty and a central executive task (Baddeley, 1986). The postural stances included standing with feet shoulder width apart and standing with feet in a tandem position. For the shoulder width stance, changes in postural sway occurred in the sagittal plane, whereas for the tandem stance, changes occurred in the frontal plane. These modifications were characterized by an increase in frequency and decrease in amplitude of sway indicating a tighter control of postural sway. Substantial changes were found between no mental task and all of the working memory tasks, but no significant variations were found between the different types of working memory tasks for all dependent variables and both postures (Dault et al., 2001a).

The effect of low and high mental load tasks on postural control was examined by Yardley et al. (2001). Baseline levels of postural sway and mental task performance were compared with levels obtained during concurrent execution of both tasks. Reaction times on low load mental tasks grew progressively longer as the balancing task increased in difficulty and accuracy declined during the high load mental tasks. Postural sway was generally unaffected by mental activity. Based on the results obtained, it was concluded that the interference between mental activity and postural control can be attributed principally to general capacity limitations, and is hence proportional to the attentional demands of both tasks.

Findings by Brown (1999) indicate that execution of an attentionally demanding cognitive task (counting down by threes) may interfere with a concurrent stepping task. Recovering an upright stance, by implementing a stepping response, was found to be attentionally demanding, more so in older adults as compared to younger adults. This research suggests that in a dual-task context, an increased risk for loss of balance and falls may result if sufficient attentional resources are not allocated to ensure postural recovery. Results of research performed by Shumway-Cook et al. (1997) also suggest

that during the concurrent performance of a cognitive and postural task, decrements in performance are found in the postural stability measures rather than the cognitive measures. When postural stability was compromised, even simple cognitive tasks further impacted balance and increased postural sway. The allocation of attention during the performance of concurrent tasks is often complex; dependent on many factors including the nature of both the cognitive and postural task, the goal of the individual and the instructions provided.

Prioritization between tasks may account for differences in reaction times between groups concurrently performing a postural task. Reaction times were longer during concurrent tasks (verbal response to an auditory choice reaction time stimulus) as compared to a single task situation (platform perturbation), but not identical between the young and older groups of participants. Results suggest that in the dual task situation older adults may prioritize step recovery over cognitive task response. Older adults responded to the first tone after the recovery step was completed whereas young adults responded earlier, during the weight shift phase of the step recovery (Brauer, Woollacott, and Shumway-Cook, 2002). Similarly, Stelmach (1990) found that when elderly individuals' attention was occupied by a mathematics task, recovery of postural instabilities took longer because recovery from these instabilities demanded mental capacity. However, this impairment was not found for the young subjects (Stelmach et al., 1990). Redfern et al. (2001) concurred that the challenge presented by an information processing task (reaction task) did not have an effect on postural sway for young subjects, however, older subjects' performance of a concurrent information processing task was associated with increased postural sway.

Contrary to previous research in which postural sway increased with the addition of a cognitive task, Hunter and Hoffman (2001) concluded that young adult participants demonstrated less postural sway in the cognitive (memory task) conditions than during the balance-alone conditions. Significantly more COP variability was observed in the no cognitive condition.

2.6.2. Subjective Assessment of Postural Stability

The risk of falling and injury are prominent in the lives of all people, particularly the elderly and certain occupational sectors (e.g. construction). A substantial amount of the original research performed in the area of postural stability, particularly subjective assessment, has centered on measuring fear of falling in the elderly. In addition to a possible loss of function after a fall due to physical trauma, psychological trauma, sometimes called fear of falling, may result in a self-imposed decline in activity and function not necessitated by physical disabilities or injury (Kellogg International Work Group, 1987; Vellas, Cayla, Bocquet, de Pemile, and Albarede, 1987). Tinetti et al. (1988) reported a study in which almost 50% of fallers admitted to a fear of falling; 25% of these fallers acknowledged avoiding activities because of this fear.

Individuals seem to enforce tighter control over center of mass kinematics when the potential consequences of imbalance are more severe (Brown and Frank, 1997). Thus, if the individual maintains a fear of falling, postural stability may be affected. Adkin et al. (2002) investigated the fear of falling and postural threat on control of posture and movement during a voluntary rise to toes task in healthy subjects. It was shown that performance was modified during the condition at the edge of the platform (highest threat condition). Results suggest that alterations in postural adjustments may be magnified by the fear of falling while changes in timing of postural adjustments may reflect underlying pathology (Adkin et al., 2002).

Falls, their prediction, and prevention have been extensively examined using physical parameters, most notably measures of balancing ability. Psychological factors must also be regarded, particularly given that balance test performance appears to be affected by individual apprehension (Myers, Powell, and Maki, 1996). People tend to avoid activities for which they distrust their capabilities; therefore, a relationship should exist between the measures of avoidance and capabilities (Myers et al., 1996). It is not clear as to the effects that a fear of falling or feelings of postural instability has on an individuals' performance of tasks, although Maki et al. (1991) found that subjects reporting fear of falling demonstrated greater COP measures under several balance test conditions using a force platform.

One approach to the assessment of fear of falling is simply to ask individuals whether or not they are afraid. An individual's rating of their fear of falling has the advantage of being straightforward and simple and lending itself easily to generating prevalence estimates (Lawrence, Tennstedt, and Kasten, 1998). However, global self-reports can be imprecise because standards used to make judgments tend to vary among individuals.

The question "are you afraid of falling?" was used initially in research studies with a "yes/no" or "fear/no fear" response format. This measure was later criticized for its limited ability to detect variability in degrees of fear and because it may express a generalized state of fear that does not directly reflect fear of falling (Legters, 2002). Several authors have expanded the response choices to provide hierarchies of responses to better reflect the degree of fear (Legters, 2002).

An alternative approach is to examine individuals' self-efficacy by asking them about their perception of falling within a variety of specific situations or performing particular tasks. Self-efficacy refers to an individual's perception of capabilities within a particular domain of activities (Bandura, 1978; Bandura, 1986). Efficacy within a domain of activities is defined as the average or sum of activity-specific efficacies (Bandura, 1986). Based on the idea of self-efficacy, Myers et al. (1996) demonstrated an association between physical ability and perceived capabilities.

Self-efficacy is a concept that is based upon strong theoretical assumptions about the cognitive process that underlies emotions (Bandura, 1986). Objective, reliable, and applicable assessment strategies have been developed to measure efficacy in a range of activities, including physical performance (Lee, 1982). A distinct advantage of the measurement of self-efficacy is the ability to utilize continuous scales. This expands the concept of fear from a dichotomous entity (i.e. either one is fearful or one is not) to one that is continuous (i.e. how much confidence does one have in one's ability to avoid a fall during specific activities). Finally, efficacy may be correlated to functional decline since persons with low perceived efficacy in an activity tend to avoid the activity (Bandura, 1982). Lawrence et al. (1998) recognized the relationship between functional disability and fear of falling. When analyzing specific functional domains, higher levels of fear of falling were associated with higher levels of physical dysfunction. According to

Bandura's efficacy framework, perceived capability rather than actual physical ability may be more predictive of behavior in a given domain (Bandura, 1991).

Efficacy is a promising approach to quantifying the psychological component of balance-related behavior (Myers et al., 1996). Previous research has relied on direct queries, wherein subjects rated their fear of falling qualitatively and quantitatively (Arfken, Lach, Birge, and Miller, 1994; Howland, Peterson, Levin, Fried, Pordon, and Bak, 1993; Maki et al., 1991; Walker and Howland, 1991). An increase in fear of falling has been related to decreased satisfaction with life, increased frailty, depressed mood, decreased mobility and social activities (Arfken et al., 1994). Howland (1993) used a 4-point scale as a response format with the following anchors: not at all afraid, slightly afraid, somewhat afraid, and very afraid. Asking individuals to rate various concerns using the 4-point scale assessed fear of falling. Maki et al. (1991) found that individuals who expressed a fear of falling exhibited significantly poorer performance in spontaneous sway tests. Furthermore, based on results obtained, the authors suggest that a fear of falling may confound studies of postural control and falling.

Tinetti et al. (1990) developed the Falls Efficacy Scale (FES). It was designed to assess the degree of perceived efficacy at avoiding a fall during each of 10 relatively nonhazardous activities of daily living. Confidence in accomplishing each activity without falling is assessed on a 10-point continuum with a higher score equivalent to lower confidence of efficacy. Scores for each activity range from 1 (completely confident) to 10 (not at all confident). The FES score is the sum of scores on each of the 10 activities. Thus, the possible scores range from 10-100. Scores have been shown to increase for individuals who express fear of falling and increase even more for those who admitted to being afraid and avoiding certain activities (Tinetti et al., 1990).

Powell and Myers (1995) developed the Activity-specific Balance Confidence (ABC) Scale, to address some of the concerns and limitations of the original FES. The ABC Scale consists of a 16-item questionnaire that includes 4 items from the original FES, as well as an expanded range of more difficult activities in the area of reaching, shopping, and walking. Individuals rate their balance confidence on a visual analog scale (0-100). Zero represents no confidence, while 100 indicates complete confidence in performing the activity (Legters, 2002).

In contrast to the FES, the ABC Scale has greater item specificity and a wider continuum of item difficulty, including situations and activities of daily living (ADLs) performed outside the home. As with the FES, the ABC Scale assumes that the fear of falling represents a unitary construct that varies only with respect to the difficulty of the task being performed (Hill, Schwarz, Kalogeropoulos, and Gibson, 1996). The ABC Scale, more so than the FES, is able to discriminate between individuals who are afraid of falling and thus avoided activities, and those who did not avoid activities (Legters, 2002).

The original version of the FES measured the fear of falling in almost exclusively indoor activities. Hill et al. (1996) hypothesized that the scale may be limited in its usefulness in identifying early stages of fear of falling in active community-dwelling older people. A Modified Falls Efficacy Scale (MFES) was developed that contained the original 10-activity FES and four additional activities. Falls efficacy was rated on a 10-point visual analog scale for each activity. Percentages were marked along the scale at 0%, 20%, 40%, 60%, 80% and 100%. The MFES was shown to be a simple, quick, easy-to-administer, and reliable clinical evaluation tool.

The Survey of Activities and Fear of Falling in the Elderly (SAFE) was developed to assess fear of falling, based on the premise that there are negative consequences to this fear. Consequences include activity restriction or poor quality of life. This survey examines 11 ADLs, instrumental activities of daily living, mobility tasks, and social activities. Exercise and social activities were added because it was hypothesized that avoiding these activities might signal early onset of fear of falling (Lachman, Howland, and Tennstedt, 1998). Individuals are asked numerous questions concerning each task that they are to rate using a 5-point scale (0-4). The fear of falling score was the sum of all responses. Similar to the ABC Scale, this tool was able to discriminate between those who restricted their activity because of a fear of falling and those who did not place any restrictions on their activities (Lachman et al., 1998).

Lawrence et al. (1998) developed two scales to further investigate the premise of fall-related efficacy: Perceived Control Over Falling and Perceived Ability to Manage Falls and Falling. Perceived Control Over Falling has 4 items that focus on control over the environment and the person's mobility and ability to do things to prevent falls. The scale's 5-point Likert-type response format ranges from "strongly disagree" to "strongly

agree”. Perceived Ability to Manage Falls and Falling is a 5-item scale that assesses people’s beliefs about managing falls. A 4-point scale ranging from “not at all” to “very sure” is used. Research based on these scales demonstrates that individuals with a higher perceived ability of managing falls also had a lower fear of falling (Legters, 2002).

It is imperative that risk factors for falls and the degree to which fear of falling can affect mobility and constrain activities of daily living be identified (Walker and Howland, 1991). Fear of falling has been consistently correlated to an increase in restriction of activity (Howland, Lachman, Peterson, Cote, Kasten, and Jette, 1998; Howland et al., 1993; Luukinen, Koski, Kivela, and Laippala, 1996; Petrella, Payne, Myers, Overend, and Chesworth, 2000; Tinetti, Mendes de Leon, Doucette, and Baker, 1994). Fear of falling can compromise quality of life by limiting mobility and social interaction (Howland et al., 1993; Kellogg International Work Group, 1987). It is important to expand upon the current research and identify the degree to which the assessment of postural instability affects all individuals, expanding applicability to potentially hazardous occupational settings.

When necessary, individuals can be taught to recognize risky behaviors associated with falls and help investigate safer approaches to their activities (Walker and Howland, 1991). It is unclear as to whether individuals can properly identify the level of risk associated with tasks involving the maintenance of balance. Therefore, it is necessary to assess the capability, if any, of normal individuals to perceive and evaluate their own stability during short periods of quiet stance under different sensorial conditions and to determine whether a self-evaluation score could be a relevant variable for further use.

Schieppati et al. (1999) analyzed the congruity between subjective reports and objective stabilometric findings. This was accomplished by using a simple subjective scale of steadiness. At the end of each trial, individuals were asked to evaluate their subjective feeling of the quality of steadiness throughout that particular trial. The evaluation took the form of a score, ranging from 0 (worst) to 10 (best). Half points and quarter points were allowed, to distinguish trials with small differences. The stabilometric measures were: (1) the position of the instantaneous center of foot pressure (CFP), (2) the projection of the CFP on the sagittal and frontal planes, (3) the mean position of CFP during the trial, (4) the sway path, or distance covered during the trial by

the moving CFP, (5) the sway area, or surface swept during the trial by the shift of the line joining the mean CFP to the moving CFP. Results showed that the scores attributed to stability during an upright stance reflected the actual stabilometric sway values. It was determined that individuals were able to score their sways according to an absolute criterion, as opposed to using their “typical” area during a quiet stance as a reference. Thus, the use of a subjective scale displays potential as a tool for quantifying the self-evaluation of body sway and balance.

While investigating the influence of fear of falling on the control of posture, Adkin et al. (2002) adapted the subjective scale developed by Schieppati et al. (1999) to measure the individuals’ perceived postural stability during a series of rise to toes trials. Ratings were expressed as a percentage ranging from 0% (I did not feel stable at all) to 100% (I felt completely stable). Results showed that subjective ratings of stability were significantly different for the four levels of postural threat, with subjective ratings decreasing as the postural threat increased. The findings suggest that alterations in the magnitude of the postural adjustments and voluntary movement may be magnified by fear of falling (Adkin et al., 2002).

The subjective scale developed by Schieppati et al. (1999) was found to be (1) valid, (2) sensitive, (3) accurate, (4) simple, (5) there would be no harm for the individuals if one end of the scale was overemphasized, (6) easily applicable, and (7) displays interval properties. The criteria of self scoring postural stability depend on the integration of the peripheral information in the individuals’ egocentric representation of the space within which their body moves. Schieppati et al. (1999) hypothesized that individuals are able to evaluate their sway as a whole, putting into operation the same neural mechanisms that allow us to psychophysically evaluate the intensity of other more simple stimuli such as sound or weight (Gescheider, 1985). It is possible that individuals can evaluate the effort necessary to correct their posture during moment-to-moment adjustments of the force level in the antigravity muscles (Schieppati, Hugon, and Grasso, 1994).

Prevention of falls remains an essential and perhaps even a critical task. There is an important need for methods to evaluate existing and new prevention strategies, and more generally to determine factors that lead to falls. Since most occupational falls

appear to be related to loss of balance or impairment of balance control, a better understanding of balance can facilitate fall prevention, factors that adversely affect balance, and interventions that can promote better balance.

2.7. Research Framework

The tasks used in dual-task paradigms can require various levels of attentional resources to achieve a particular level of performance. Kahneman (1973) proposed a model of attentional capacity that assumes a single undifferentiated pool of limited resources available during multi-task situations. The determination of workload is not dependent on the types of tasks performed, as long as they are structurally dissimilar. In addition, he asserts that individuals can allocate this capacity among concurrent activities. Activities fail or performance degrades because the demands of the tasks are beyond the capacity of the individual or because the allocation policy channeled available capacity to other activities. The definition of workload used within this study considered demands relative to capacity while achieving a particular level of performance (Hart and Staveland, 1988). Workload is represented by an overall rating, not differentiated based on resources or channels. Therefore, assessment tools were chosen that provided one overall rating or measure for the domain of interest.

Recent research using a dual task paradigm suggests that sensorimotor processing requires attentional resources. Yardley et al. (2001) investigated the interference between mental activity and postural control. Interference was attributed to general capacity limitations and proportional to the attentional demands of both tasks. Evidence indicates that a minimal amount of attention is required to perform well-learned postural stances, while more difficult and novel postural stances required additional attentional resources and increased interference with the concurrent cognitive task.

The main goal of this study was to examine the factors that affect workload assessment and performance during activities requiring mental and physical demands. The effects of different types of tasks (mental and physical) and the impact of varying levels of difficulty within the tasks were investigated to determine the influence on workload assessment and performance. The purpose was to provide greater insight as to which combination of activities, and at what difficulty level, required attentional

resources beyond the capabilities of the individuals and investigate the consequences of the strategies employed to complete the time-shared tasks. In addition, the sensitivity and of common subjective assessment tools was investigated. It was hypothesized that the type of task would not be important and dual-task interference would be due to a general capacity limitation. Greater interference was expected to be associated with tasks of increased difficulty.

3. INTERACTIVE EFFECTS OF PHYSICAL AND MENTAL WORKLOAD ON SUBJECTIVE WORKLOAD ASSESSMENT

3.1. Methods and Materials

3.1.1. Overview

Development of more comprehensive workload assessment tools depends on understanding the effects of physical and mental activity on an individual's perception of workload and ability to perform required tasks. Such assessment tools are important, however, since individuals are often expected to perform physically demanding tasks concurrent with mental demands. An example is the modern use of head mounted displays during infantry combat. The effectiveness of existing workload assessment methods has not been adequately evaluated in situations demanding both mental and physical activity. Because of their ease of use, though, subjective measures are of predominant interest for workload assessment, including those requiring concurrent completion of both physical and mental tasks.

Select subjective assessment methodologies were evaluated quantitatively during laboratory-based experiments in which physical and mental workloads were varied. Concurrent execution of mental and physical activity was required, since it was desired to be able to measure mental workload, physical workload, and also evaluate their interaction. Experimental conditions were performed over a wide range of mental and physical loading levels, including various physical loads and arithmetic tasks, encompassing different demands and attentional requirements. The influence of concurrent activity on performance and subjective assessment of workload was investigated.

3.1.2. Experimental Goals

This experiment was designed to evaluate the effects of mental demands on the subjective assessment of physical workload and the effects of physical demands on the subjective assessment of mental workload. In addition, the effects of combined mental and physical demands on performance were evaluated. A lifting task was used to

represent physical workload, while arithmetic tasks were used to represent mental workload. The goals of this research were to:

1. Determine the effect of varying weights of lift on the subjective assessment of constant mental workload and performance of mental tasks.
2. Determine the effect of arithmetic operations of varying difficulty on the subjective assessment of constant physical workload and performance of physical tasks.

3.1.3. Experimental Design

The experiment was a two-factor repeated measures design. Two independent variables were manipulated and three classes of dependent measures recorded. Amount of load lifted and type of arithmetic task were the independent variables. Participants performed tasks in 15 separate conditions. The condition involving no physical and no mental load was not included in the experimental procedures.

Each condition, comprising a physical and mental task, lasted for four minutes, with a minimum of two minutes rest provided between conditions. Participants were asked to provide mental and physical workload assessments using several subjective assessment techniques, specifically the Borg CR10 Scale, Visual Analog Scales (VA Scale) and National Aeronautical and Space Administration Task Load Index (NASA-TLX). These methods were selected because of their ease of use and extensive application during previous experimental research. Workload levels were also monitored using objective measures, specifically heart rate and heart rate variability. Performance on the mental and physical tasks was recorded for all conditions.

3.1.4. Independent Variables

3.1.4.1. *Mental Activity*

Addition, subtraction, and multiplication tasks (see Table 3) were used to achieve four intensity levels (no load, low, medium, high). A list of pairs of numbers was created for each operation using a random number generator. Random ordering of these lists was used for all conditions involving the same operation. Examples of the numbers used during the arithmetic tasks are in Appendix A. Each task entailed verbal presentation of

two numbers by the experimenter that were then appropriately manipulated by the participant, who then stated the answer. The task was repeated until a correct response was provided and a new pair of numbers was then presented immediately following.

Table 3. Arithmetic tasks representing four different mental workload levels.

Mental Workload	Arithmetic Task
No Load	No task performed
Low	Addition of two numbers between 1-20
Medium	Subtraction of two numbers between 21-99
High	Multiplication of a number between 4-9 and a number between 11-50

The specific mental activity (arithmetic) was chosen since it required cognitive processes common to many daily tasks (e.g. recall) and was easy to implement without interfering with the concurrent physical activity (described below). Various arithmetic tasks have also been used in previous studies (e.g. Brody, Maier, Montoya, and Rau, 1994; Luximon and Goonetilleke, 2001; Maki and McIlroy, 1996), and Kahneman (1973) refers to arithmetic as being a highly demanding mental task, requiring rehearsal in addition to the cognitive processes required to perform the operation.

In a pilot study (see Section 3.2.1), it was verified that the four mental tasks described above produced four distinct levels of mental workload as determined by the participants' subjective assessment of the difficulty of the tasks, although the level of effort required varied depending on the abilities of the participants. In particular, the multiplication task was not proposed as a maximum workload level; rather, it was 'relatively' high in relation to the other tasks.

3.1.4.2. *Physical Activity*

Physical activity consisted of lifting and lowering a box containing a range of weights. Boxes were lifted from an indicated location on the floor to an indicated location on the surface of a table, and then returned to a position on the floor. There were four workload levels (no load, low, medium, high). Altering the weights of the load

controlled the intensity of the task (Table 4), with specific weights selected as a percentage of the individual’s body weight. Normalized, rather than absolute weights, were used to account for individual strength differences and allow for inter-individual comparisons.

A lifting task was chosen to maximize the generalizability of the results. This task is analogous to the physical demands required by workers in a variety of fields. In a pilot study (see Section 3.2.2), it was verified that these four load levels produced distinct levels of physical workload as determined by the participants’ subjective assessment of the difficulty of the tasks, although actual effort required varied depending on the abilities of the participants. In particular, the task with the most weight was not proposed as a maximum workload level; rather, it was ‘relatively’ high in relation to the other tasks.

Table 4. Loads lifted, representing four different physical workload levels.

Physical Workload	Load
No Load	No task performed
Low	8% of body weight
Medium	14% of body weight
High	20% of body weight

3.1.5. Dependent Variables

3.1.5.1. *Performance Measures*

Performance during the mental task was determined as the number of correct responses provided in each condition. This metric was chosen because the duration of the conditions was fixed and the presentation speed of the numbered pairs was dictated by the ability of the participant, thus reflecting the workload required. As the difficulty of the task increased, the number completed correctly is reduced due to incorrect responses and slower response times. Therefore, the consequence of incorrect responses was incorporated into this value. Furthermore, relative values, such as percentage of correct responses, do not provide any indication of the number of pairs completed.

Accuracy of box placement was used to determine performance of the physical task. Rectangular target zones were marked at each of the four placement positions. The target zones were two inches longer and wider than the boxes. Correct execution of the physical task required each of the boxes to be placed completely within the target zone. The accuracy of box placement did not vary for any of the conditions. All participants were able to place the boxes within the target zone for each trial. No further analysis concerning physical performance was performed since no factor affected physical performance.

3.1.5.2. Subjective Measures of Workload

Subjective assessments of physical workload (or perceived exertion) were obtained using the Borg CR10 Scale, which is widely used to assess whole body exertions (Borg, 1978; Borg, 1990; Borg and Noble, 1974; Noble et al., 1983; Robertson, Goss, and Metz, 1998). Subjective mental workload was assessed using a VA Scale and the NASA-TLX. The VA Scale was used to quantify the participant's assessment of mental workload in each condition (Noble and Robertson, 1996). The NASA-TLX provided a subjective workload score based on a weighted average of ratings on six subscales or dimensions (Eggemeier and Wilson, 1991). An additional VA Scale, similar to the Overall Workload Scale (Hill et al., 1992), was used to quantify the participant's overall perception of workload (physical and mental) in each condition.

NASA-TLX scores were also reevaluated without considering the physical dimension, in order to provide a rating not influenced by a direct physical subjective assessment. The values associated with the physical dimension were separately evaluated as an additional physical workload measure. In addition, NASA-TLX scores were calculated without adjusting for the weights provided by the individuals for the six dimensions. Moroney et al. (1995; 1992) determined that the weightings do not significantly affect the resulting workload scores.

3.1.5.3. Objective Measures

Objective physical and mental workload estimations were determined using heart rate and heart rate variability, commonly interpreted as physiological representations of the reaction of the circulatory system to physical and mental demands, respectively

(Meshkati, 1988; Miyake, 2001; Wickens et al., 1998). A Polar™ S810 Heart Rate Monitor was used to measure heart rate. Recording began prior to the initiation of each task, continued throughout the task, and ended at the conclusion of the condition. The heart rate monitor identified each heart beat and calculated heart rate and interbeat intervals. Prior to analysis, the heart rate data was filtered using the Polar™ S810 Performance Software 3.0 to remove erroneous data points. Moderate levels of filtering were used, although a description of the specific algorithm employed within the software was not available. Heart rate values were normalized, using the participant's maximum and minimum (resting) heart rates, and plotted versus time for each of the conditions. Maximum heart rate was calculated as 220 bpm minus the participant's age (Franklin, 2000). HRV was defined as the standard deviation of the participant's heart rate during the last minute of each condition (Kamath and Fallen, 1993).

3.1.5.4. *Participants*

Thirty volunteers, between 18 and 24 years of age, were selected from the university community. The mean (sd) age of the participants was 20.7 (1.15) years old. This sample size was sufficient to detect a difference in the means, for each dependent measure, of one standard deviation 90 percent of the time when a difference was present, with a Type I error of 0.05. There were an equal number of female and male participants. Participants of a homogeneous age group were used to minimize possible age effects. In addition, all participants were university undergraduate students, reducing the possible effects caused by differing educational background levels. All participants were in good health and had no self-reported history of musculoskeletal injuries within the last 12 months. Reasonably fit individuals that could lift and carry 20% of their body weight participated. The mean (sd) body mass of the participants was 66.8 (18.0) kg.

3.1.6. Experimental Procedures

At the onset of the experiment, participants received verbal and written information concerning the purpose, methods, and intent of the experimental procedures using a standardized set of instructions. They were given an opportunity to ask any questions pertaining to the study, and then asked to read and sign an informed consent approved by the Virginia Polytechnic Institute and State University IRB.

Following completion of the informed consent, participants were verbally presented with 10 arithmetic problems from each difficulty level used within the study. A set of numbers was determined using a random number generator (Appendix B) and five minutes was provided to complete each list. Subsequent pairs of numbers were not presented until each problem was answered correctly. Participants were instructed to perform the arithmetic tasks as quickly as possible while minimizing errors. This preliminary set of tasks served as a screening tool; participants unable to complete the task were not allowed to continue with the experimental procedures. Learning or practice effects within the experiment due to lack of familiarity with performing mental arithmetic were reduced by providing participants an additional opportunity to familiarize themselves with the mental tasks by completing additional problems presented as in the screening tool.

The Polar™ S810 Heart Rate Monitor was placed on the participant's torso against the skin and the receiver (watch) on the wrist. Heart rate was then recorded for five minutes while a seated position was maintained. Resting heart rate was the minimum heart rate, averaged over 15 second intervals, obtained during this five minute period.

A practice session was provided to allow the participants an opportunity to familiarize themselves with the lifting tasks. Participants were not instructed to use any specific lifting technique, although they were instructed to grasp the handles of the boxes with both hands. Boxes of various weights were lifted from an indicated location on the floor to an indicated location on the surface of a table and then returned to a position on the floor. The vertical lifting distance was 750 mm (standard table top). The width (the distance between the hands) of the boxes was 600 mm, while the depth (the distance away from the body) of the boxes was 340 mm. Cut outs in the lateral faces served as handles. The subjective workload assessment scales (Borg CR10 Scale, VA Scales and NASA-TLX) were explained following the practice session and prior to the execution of the experimental conditions.

Participants performed each of the conditions for four minutes while their heart rate was recorded. The duration of conditions was determined in a pilot study as sufficient to achieve steady state in heart rate (see Section 3.2.3). To prevent any

confounding influences related to ordering (e.g., learning), the presentation order of the conditions was counterbalanced. When instructed to begin, the participant lifted a box from the floor and placed it on an indicated spot on the surface of the table. They then lowered a second box from the table and placed it at the position on the floor left vacant by the first box. Participants continued to lift and lower boxes in this alternating fashion (Figure 10) at a fixed pace of five lifts per minute. Consistent pacing was achieved by having participants follow computer generated auditory signals. It was emphasized to the participant that maintaining the pace was required.

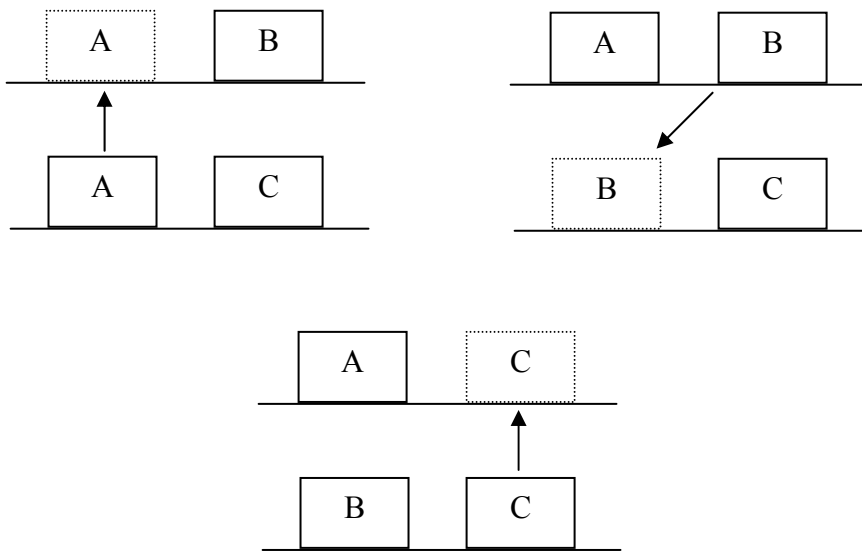


Figure 10. A front view of the orientation of the boxes during the lifting and lowering task. The first three steps are illustrated.

Concurrent with the physical activity, numbers were recited that the participant added, subtracted, or multiplied depending on the condition. As participants performed the operation they said their answer, with the experimenter repeating the pair of numbers after an incorrect response until a correct response was given. The next set of numbers was provided immediately following a correct response, and mental activity continued until the end of the condition. The number of arithmetic tasks completed correctly was recorded. Although the physical task was not proposed as being more important than the

arithmetic task, it was emphasized that the participants could not change the pace of the physical task but that no time limit existed for completion of the arithmetic problems.

At the conclusion of each condition, a rest period of at least two minutes was provided, which minimized cumulative mental and physical fatigue. During this rest period the four subjective workload assessment tools (Borg CR10 Scale, Overall VA Scale, Mental VA Scale and NASA-TLX) were completed. The entire experiment took approximately 2 ½ hours per participant.

3.2. Pilot Results

Two pilot studies were performed to address questions that arose during initial experimental design. After the development of the mental and physical tasks, it was necessary to determine levels that were perceived as four distinct loads. Subsequent to the formation of the activities performed, the duration of the trials also needed to be determined. This section describes the pilot studies and the conclusions drawn from the data obtained.

3.2.1. Levels of Mental Activity

A pilot study was performed to determine four distinct mental workload levels. The intention was to develop arithmetic activities that required distinct levels of workload but did not prevent the execution of the physical activity. In addition, basic operations were chosen so as not to preclude the use of a substantial segment of the population. Four participants, two males and two females, performed each of the mental activities (addition, subtraction, multiplication) for five minutes. No physical activity was performed. It was assumed that no mental activity was distinctly different from any condition involving arithmetic. VA Scale ratings, representing perceived mental workload levels, were collected at the end of each condition (Figure 11). An ANOVA ($\alpha = 0.05$) indicated statistically significant differences in the VA Scale ratings among the three conditions. Post hoc comparisons of the means of the three groups, using the Tukey-Kramer HSD ($\alpha = 0.05$), confirmed that the three operations created conditions that were assessed as three distinct workload levels.

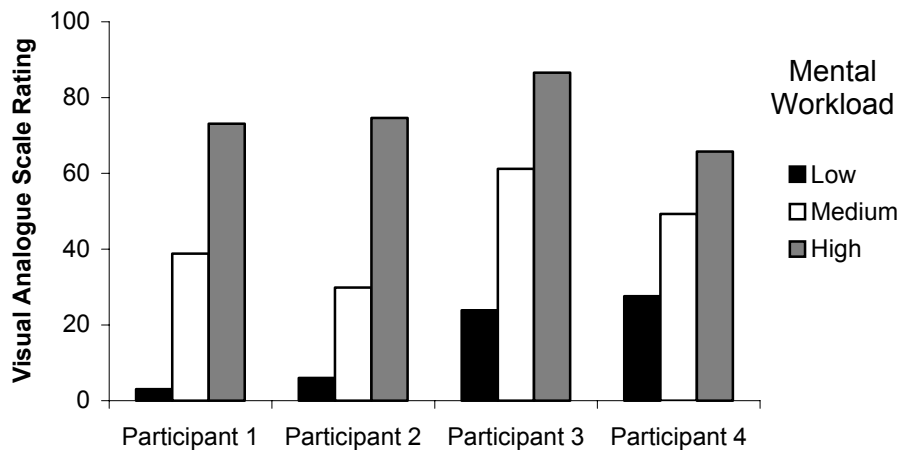


Figure 11. Visual Analog Scale ratings from the pilot study for each of the mental workload levels (low, medium, high) corresponding to the arithmetic operations of addition, subtraction, and multiplication.

3.2.2. Levels of Physical Activity

A second pilot study was performed to determine four distinct physical workload levels. The intention was to determine light loads that could still be perceived as different, although restrictions existed due to the construction of the boxes (minimum mass = 4 kg). The weight lifted was minimized in order to reduce the risk of injury to the participants and physical fatigue.

Four participants, two males and two females, performed the lifting task previously described at each load condition (low, medium, high) for five minutes. The masses chosen were 8%, 14%, and 20% of the participant's body weight. No mental activity was performed. It was assumed that no load was distinctly different from any condition involving lifting. Borg CR10 ratings were collected at 30 second intervals and then averaged within each condition (Figure 12) to determine the subjective assessment values for each load. An ANOVA ($\alpha = 0.05$) indicated statistically significant differences in the CR10 ratings among the three conditions. Post hoc comparisons of the means of the three groups, using the Tukey-Kramer HSD ($\alpha = 0.05$), confirmed that the three load levels were assessed as three distinct workload levels.

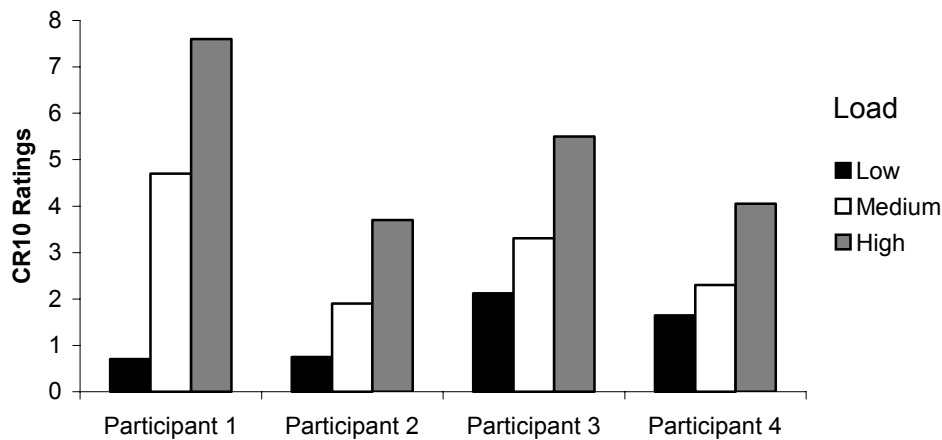


Figure 12. Borg CR10 Ratings from the pilot study for each of the three load conditions (low, medium, high).

3.2.3. Duration of Trials

The initial duration of the conditions was set at five minutes, but was found to lead to moderate-high levels of reported cumulative fatigue by the end of the experiment. A pilot study was conducted to determine if the duration of each condition could be reduced without compromising the accuracy of the data collected. Specifically, the intent was to determine the duration required for heart rate to achieve steady state in response to the physical task demands.

Four participants, two males and two females, performed each of the physical workload conditions (low, medium, high) for five minutes while their heart rates were monitored. The three physical workload levels were used in this pilot study without any mental activity, in order to minimize variability in the data due to factors not attributed to physical activity. The heart rate values were normalized, using the participant's maximum and minimum (resting) heart rates, and plotted versus time for each of the three conditions (Figure 13).

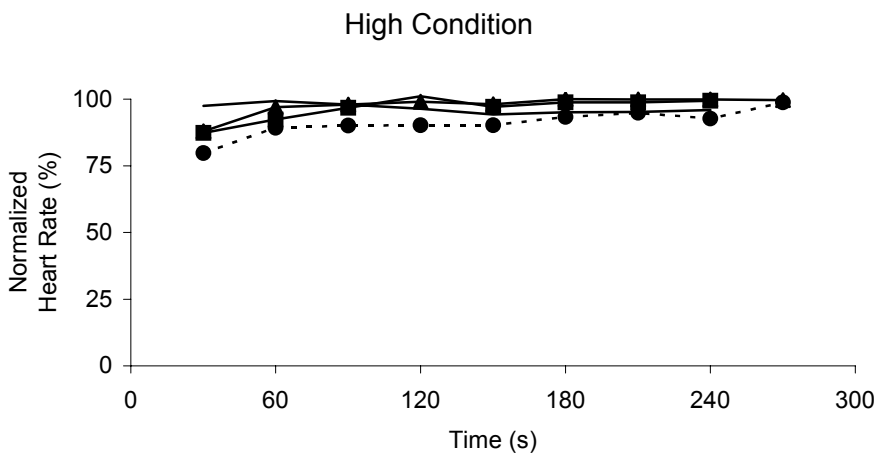
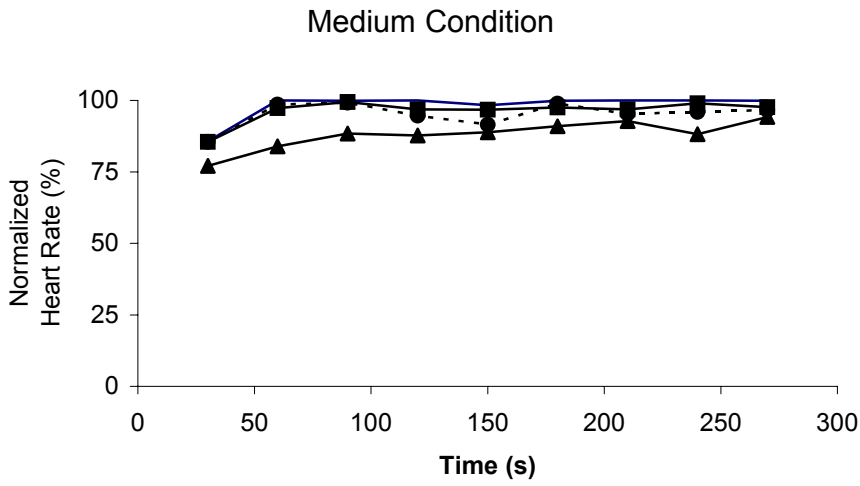
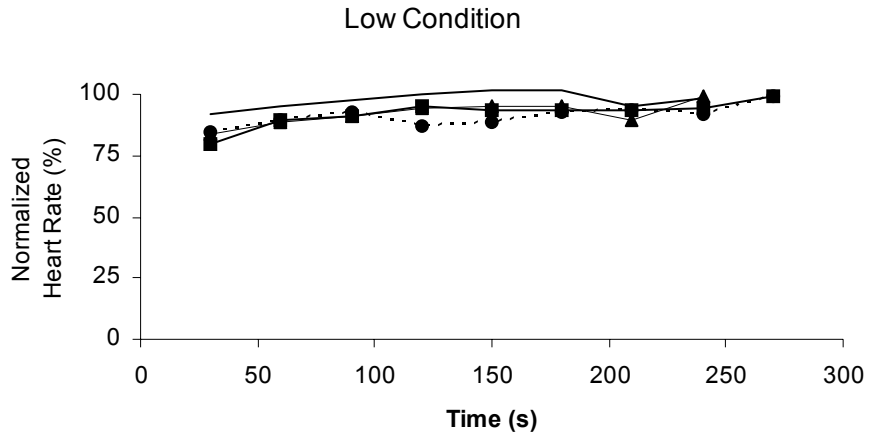


Figure 13. Normalized heart rate for each of the three physical workload conditions (low, medium, high). Each line corresponds to a different participant.

The normalized heart rate values for the four participants were averaged over 30 second intervals, and the Tukey-Kramer HSD test ($\alpha = 0.05$) was used to compare the means of each interval and determine when the heart rates stabilized. For each of the conditions, significant differences were only found between the first two intervals (0-30 and 30-60 sec). These results, along with inspection of the data trends (Figure 13), indicated that heart rate stabilized within 1-2 minutes of physical activity and then did not significantly change throughout the condition. Trial durations of four minutes were therefore considered sufficient to achieve steady state heart rate, with heart rate values for each condition determined from the last minute of data collected.

3.3. Data Analysis

Dependent measures consisted of workload levels obtained from the Borg CR10 Scale, VA Scales, NASA-TLX, heart rate and correct responses. All data were examined for normality using the Shapiro-Wilk Test, with no substantial deviations observed, thus permitting the use of parametric statistical analyses

Univariate repeated measures analyses of variance (ANOVA) were performed to evaluate the effects of physical and mental workload on workload assessment and performance, including interactions. Post hoc analyses, using the Tukey-Kramer Honestly Significant Difference (HSD) test for all comparisons, determined which changes in workload levels (e.g. no load to low) caused significant differences in assessment and performance. Objective measures (heart rate and heart rate variability) were correlated with the corresponding subjective assessment values to determine the relationships between workload levels and subjective assessments. All statistical analyses were evaluated at a significance level of $\alpha = 0.05$.

3.4. Results

The results were divided into five categories: (1) assessment of mental workload, (2) assessment of physical workload, (3) assessment of overall workload, (4) performance measures, and (5) correlations between subjective and objective assessment measures. Significant effects are identified, with p-values reported only for nonsignificant effects.

3.4.1. Assessment of mental workload

Subjective assessments of mental workload, determined by a VA Scale, consistently and significantly increased with difficulty of the arithmetic task (Figure 14), and mental workload. The increase between the medium and high mental workload levels was the only difference that was not significant. An increasing trend in VA Scale scores was also found with an increase in physical workload levels, although the effect was not significant ($p=0.14$). Ratings for the no physical load conditions were significantly different than those obtained during the other physical workload levels. No significant interaction effect between mental and physical workload was evident ($p=0.72$).

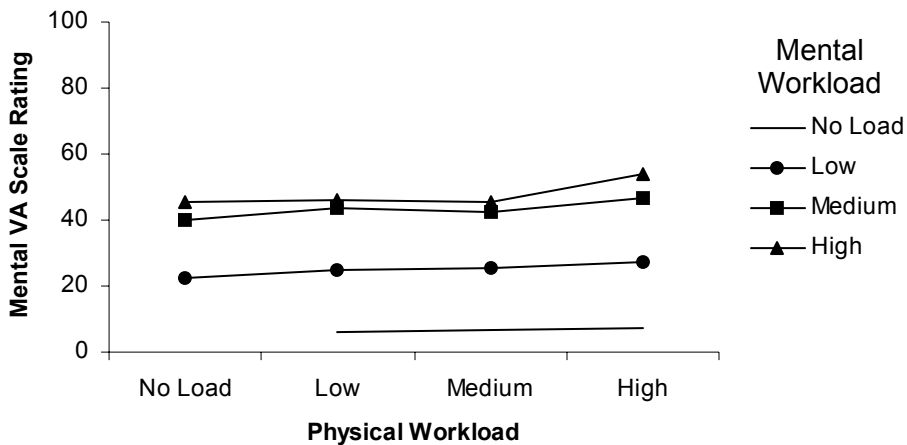


Figure 14. Mental workload assessment scores, using a Visual Analog scale.

Subjective assessments of mental workload, determined using the NASA-TLX (Figure 15), were significantly affected by both mental and physical workload. Within each mental workload level, increases in physical workload resulted in higher NASA-TLX scores, with significant differences between each level. Scores also increased within physical workload levels with increased mental workload, although pairwise comparisons indicated that the difference between the medium and high mental

workload level was not significant. There was not a significant interaction effect (p=0.99).

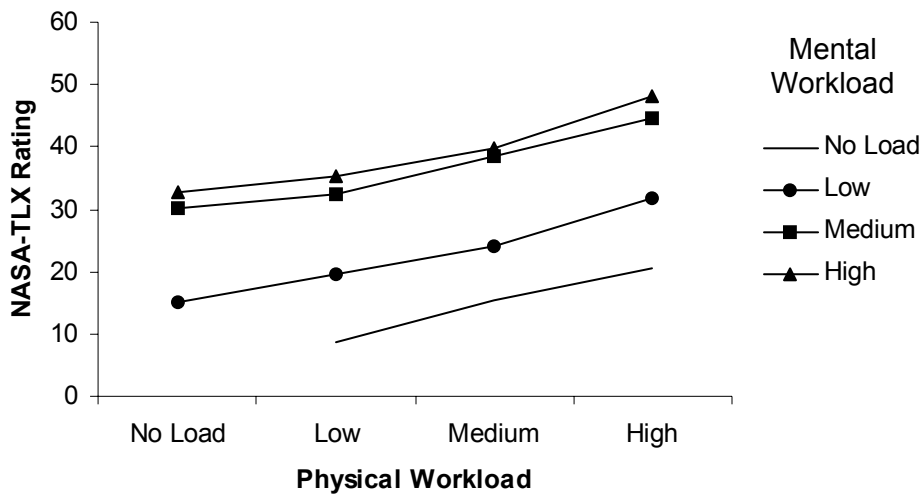


Figure 15. Mental workload assessment scores, using the NASA-TLX.

NASA-TLX ratings were recalculated after omitting the physical demand dimension. The equation for the adjusted NASA-TLX rating is shown in Equation 2. The weights (W) and ratings (R) for the five dimensions, other than physical, are included.

Adjusted NASA-TLX Rating =

$$(W_{MD} * R_{MD} + W_{TD} * R_{TD} + W_{OP} * R_{OP} + W_{FR} * R_{FR} + W_{EF} * R_{EF}) / 10 \quad (2)$$

NASA-TLX scores calculated without the physical demand dimension produced similar mental workload ratings as the original scores (Figure 16). The effects of physical and mental workload on the adjusted NASA-TLX ratings were again both significant and the interaction was not significant (p=0.99). The adjusted ratings reflected the increase in mental workload, but also increased with heavier loads.

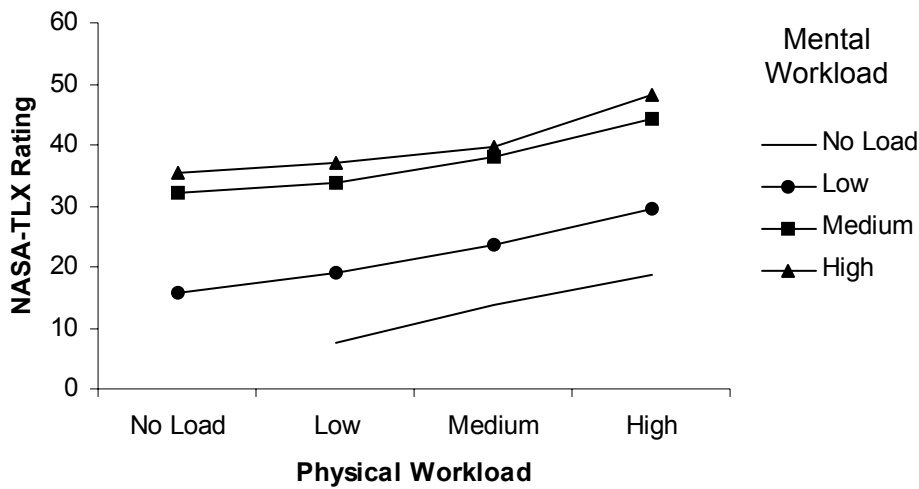


Figure 16. Mental workload assessment scores, using the NASA-TLX without the physical demand dimension.

NASA-TLX scores were recalculated without weighting the dimensions. Thereby, the ratings (R) provided for each of the six dimensions equally influenced the overall workload assessment score. The calculation of the participant's adjusted NASA-TLX rating, without accounting for the weights, is provided in Equation 3.

$$\text{Adjusted NASA-TLX Rating} = (R_{MD} + R_{PD} + R_{TD} + R_{OP} + R_{FR} + R_{EF})/6 \quad (3)$$

Mental and physical workload level had a significant effect on the adjusted NASA-TLX ratings. Larger ratings were associated with increases in mental and physical workload, although the interaction was not significant ($p=0.99$).

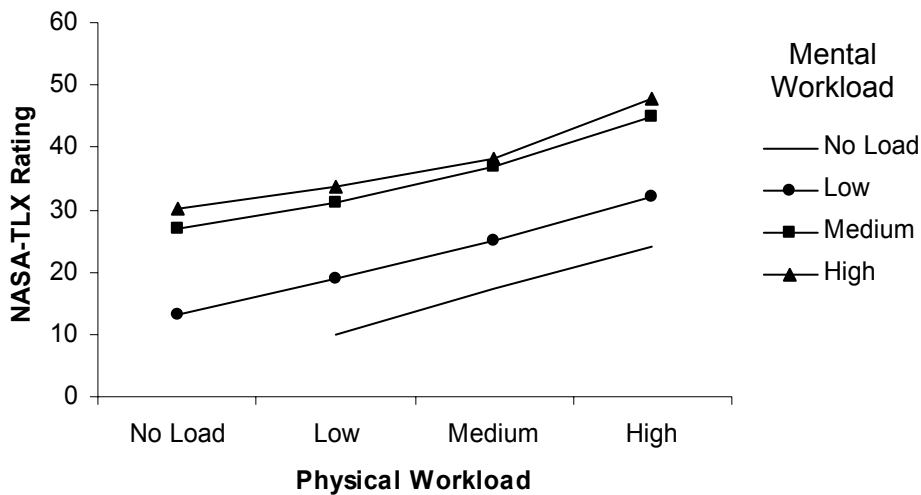


Figure 17. Adjusted NASA-TLX ratings, calculated without weighting the six dimensions, averaged across all participants for the four levels of mental and physical workload.

A significant effect of physical workload on HRV was found, and post hoc analyses indicated that it was significantly different at higher levels (Figure 18). Except for the initial increase associated with the introduction of a physical task, there was a decreasing trend in HRV as physical workload levels increased. No substantial differences in HRV were found with changes in mental workload ($p=0.24$) and no significant interaction effect was present ($p=0.53$).

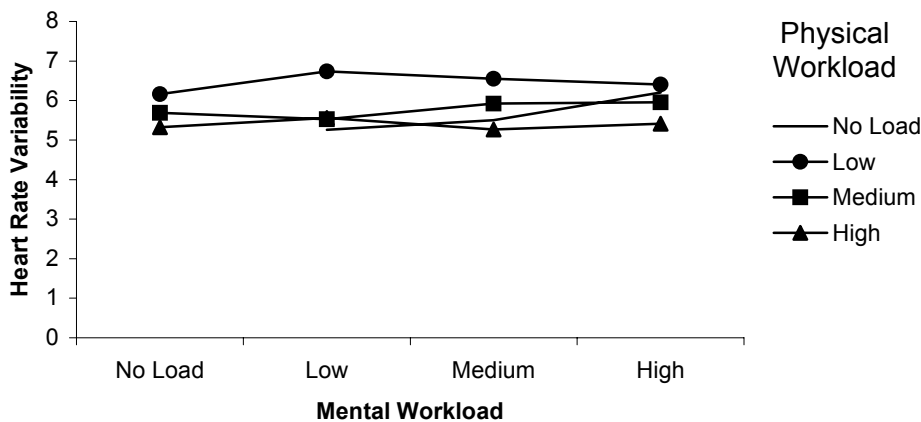


Figure 18. Objective measure of mental workload, as indicated by heart rate variability.

3.4.2. Assessment of physical workload

Perceived physical workload, as assessed by the Borg CR10 Scale, significantly increased with physical workload level (Figure 19). No consistent effect was evident with changes in mental workload ($p=0.91$). Examination of the data indicated a possible interaction effect, since ratings of perceived physical workload increased with increases of mental workload at low physical workload levels, but decreased at high levels of physical workload. This interaction, however, was not significant ($p=0.51$).

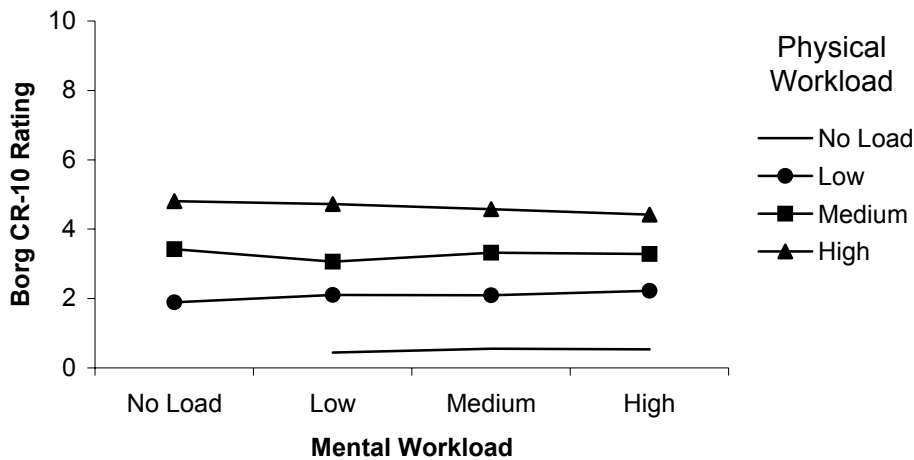


Figure 19. Overall physical workload assessment scores, using the Borg CR10 Scale.

Physical workload assessments, using the NASA-TLX physical demand dimension, significantly increased with physical workload level (Figure 20). No significant effect on the physical demand ratings was evident with changes in mental workload ($p=0.66$), nor an interaction effect ($p=0.93$).

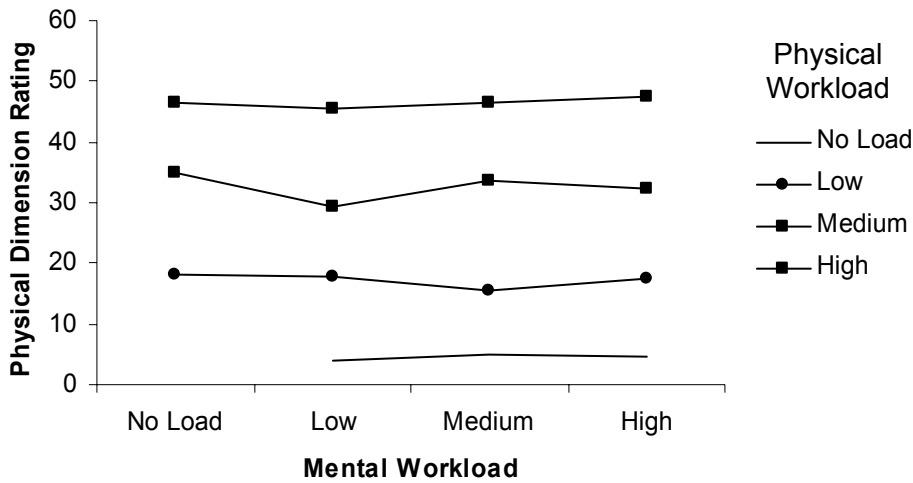


Figure 20. Overall physical workload assessment scores, using the physical demand dimension of the NASA-TLX.

The effect of physical workload on normalized heart rate (NHR) was significant (Figure 21). NHR significantly increased for each increase in physical workload level. Changes in mental workload level did not significantly affect NHR ($p=0.61$), and the interaction effect was not significant ($p=0.93$).

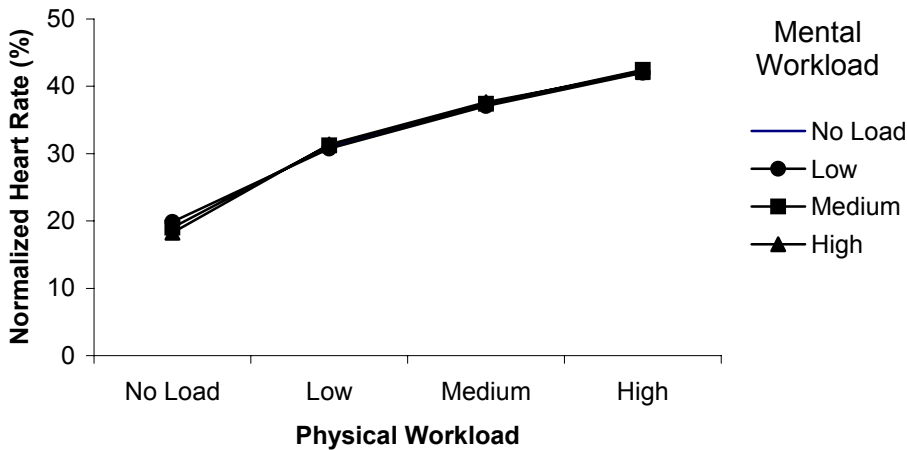


Figure 21. Objective measure of physical workload, as indicated by normalized heart rate (note, the four lines are nearly overlapped).

3.4.3. Assessment of overall workload

Subjective ratings of overall workload using a VA Scale were significantly affected by changes in mental and physical workload levels (Figure 22). Ratings consistently increased with increases in physical workload and generally increased with higher mental workload levels. The effect of mental workload, however, was not as large when physical workload was high. Pairwise comparisons indicated that significant differences in means were evident for all physical workload levels. Significant differences were verified between ratings associated with the individual mental workload levels, except between the medium and high load conditions. There was no significant interaction effect ($p=0.25$).

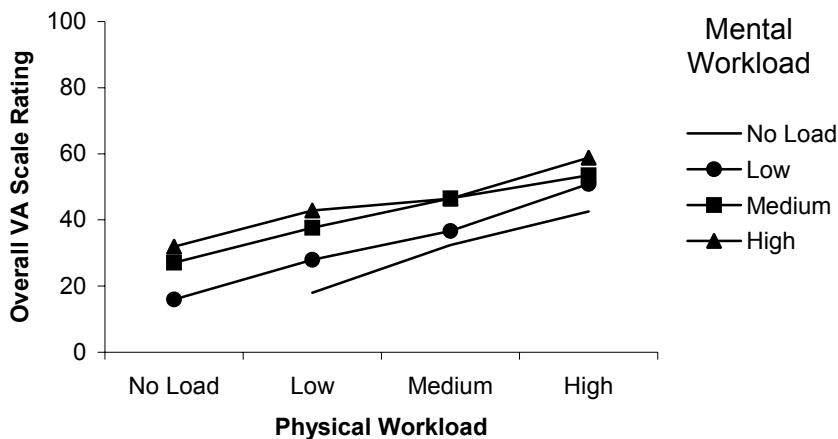


Figure 22. Overall workload assessment scores, using a VA scale, for conditions of varying physical and mental workload.

3.4.4. Performance measures

Performance, the number of correct arithmetic responses, was dependent on the level of mental workload (Figure 23), and significantly decreased as the mental workload level increased. Within each mental workload level, the number of correct responses significantly decreased with increasing levels of physical workload, although post hoc analyses indicated a non-significant difference between the low and medium workload levels.

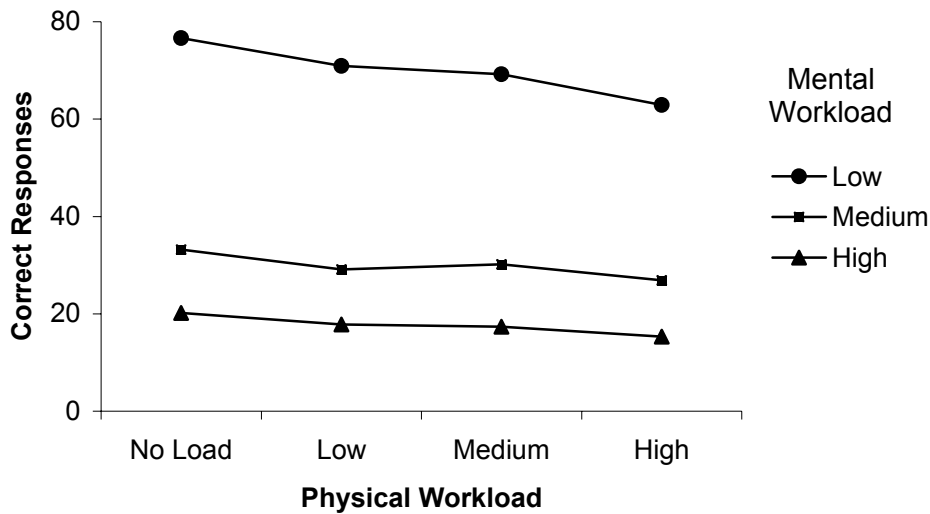


Figure 23. The number of correct arithmetic responses for low, medium, and high mental workload levels at four levels of physical workload (no load, low, medium, high).

The performance dimension of the NASA-TLX provided ratings of perceived achievement on a scale from good to poor. A significant effect of physical workload was found. Paired comparisons indicated that performance ratings for the no load condition were significantly different from all other levels, but that no other significant differences existed between levels (Figure 24). Similarly, there was a significant effect of mental workload, but the only significant differences among the pairwise comparisons were between the no load condition and conditions that included mental arithmetic. No significant interaction between mental and physical workload was found ($p=0.99$).

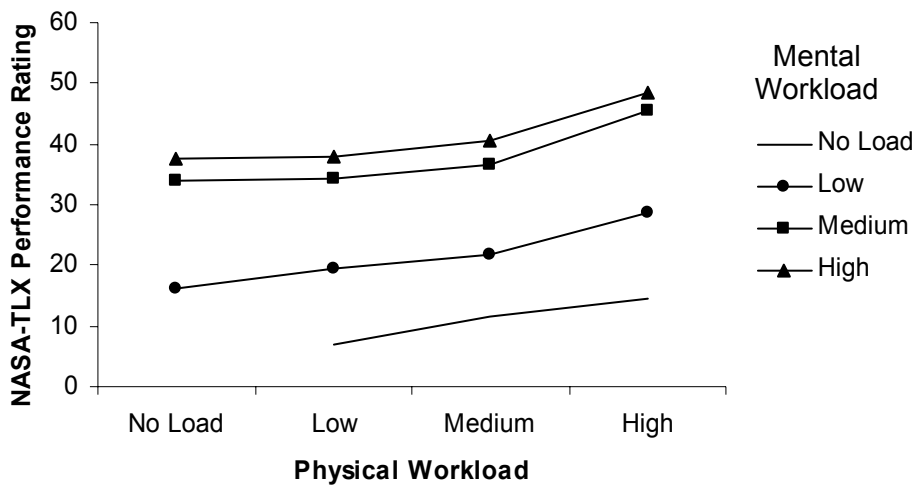


Figure 24. Performance dimension ratings for responses for low, medium, and high mental workload levels at four levels of physical workload (no load, low, medium, high).

3.4.5. Correlations between subjective and objective measures

Correlations (r) within and between the subjective and objective measures of mental and physical workload (Table 5) were determined. HRV, the objective measure of mental workload, was significantly correlated with the VA Mental ratings ($r = 0.25$, $p < 0.01$), but was not significantly correlated with the NASA-TLX scores ($p = 0.98$) used to subjectively assess mental workload. Correlations between HRV and the adjusted NASA-TLX ratings (omission of physical demand and unweighted) were not significant ($p = 0.71$ and $p = 0.97$).

NHR, the objective measure of physical workload, was significantly correlated with subjective assessments of physical (Borg CR10 ratings) and overall workload (VA Overall), with $r = 0.53$ and $r = 0.34$, respectively. NHR was not significantly correlated, however, with the NASA-TLX physical demand rating ($p = 0.59$). Ratings obtained for the physical demand dimension of the NASA-TLX, in contrast, were highly correlated with the Borg CR10 ratings ($r = 0.80$) of perceived physical workload.

Performance on the mental arithmetic tasks (correct responses) was not significantly correlated with either the VA mental workload ratings ($p = 0.51$) or HRV ($p = 0.88$). Significant correlations were all negative and ranged from $r = -0.12$ and $r = -$

0.17. These included the ratings of perceived physical workload, all NASA-TLX scores, and VA overall ratings. Performance dimension ratings of the NASA-TLX were also significantly correlated with the number of correct arithmetic responses ($r = -0.010$).

Table 5. Pearson’s Correlation Matrix (r) for Subjective and Objective Measures of Mental and Physical Workload. P-values are provided in parentheses.

Measure	VA Mental	VA Overall	NASA-TLX	Performance	NHR	HRV
Borg CR10	-0.01 (0.89)	<i>0.53</i> <i>(<0.01)</i>	<i>0.33</i> <i>(<0.01)</i>	<i>-0.14</i> <i>(<0.01)</i>	<i>0.53</i> <i>(<0.01)</i>	<i>-0.16</i> <i>(0.03)</i>
VA Mental		<i>0.60</i> <i>(<0.01)</i>	<i>0.64</i> <i>(<0.01)</i>	0.06 (0.51)	-0.11 (0.21)	<i>0.25</i> <i>(<0.01)</i>
VA Overall			<i>0.65</i> <i>(<0.01)</i>	<i>-0.14</i> <i>(<0.01)</i>	<i>0.38</i> <i>(<0.01)</i>	0.10 (0.17)
NASA-TLX				<i>-0.12</i> <i>(<0.01)</i>	<i>0.32</i> <i>(<0.01)</i>	-0.02 (0.98)
Performance					-0.08 (0.27)	-0.01 (0.88)
NHR						<i>-0.17</i> <i>(0.02)</i>

****bold and italics*** represents significance at $p \leq 0.05$

The original NASA-TLX scores were significantly correlated with the adjusted NASA-TLX ratings calculated by omitting the physical demand and not weighting the dimension ratings, with $r = 0.99$ and $r = 0.97$, respectively. Unweighted NASA-TLX scores were significantly correlated with ratings obtained using the VA Mental and VA Overall scales, $r = 0.69$ and 0.72 , respectively. NASA-TLX scores calculated without the physical demand dimensions were highly correlated with the NASA-TLX scores that were not weighted ($r = 0.97$).

3.5. Discussion

Extensive research has been performed on the separate assessment of physical and mental workload, but at present there are no validated techniques available for measuring overall workload in multi-task situations that involve substantial levels of both physical and mental workload. The present study was motivated by the need to develop a

methodology for the assessment of workload in such situations. Four mental and physical workload levels were established using concurrent tasks that were not structurally similar. Individuals were required to divide and allocate attentional resources to both tasks, while filtering extraneous stimuli that were irrelevant to the experimental tasks (e.g. enduring dispositions).

3.5.1. Assessment of mental workload

An objective measure of mental workload, heart rate variability, was collected to compare to the subjective assessments. Heart rate variability, as defined for this study, was not sensitive to changes in mental workload, though a decrease in heart rate variability was expected with an increase in mental workload (Meshkati, 1988). No significant changes in heart rate variability were present between any of the mental workload levels, indicating low sensitivity. Significant changes in heart rate variability due to increases in physical workload further decreased the utility of HRV as a measure of mental workload. Changes in heart rate has been associated with differing levels of physical workload, thus it was not surprising that heart rate variability was affected by heart rate levels (Saul, 1990). Heart rate variability parameters have been shown to be less reliable when the activity being performed caused irregular respiration patterns (Miyake, 1997). Concurrent physical demands may thus compromise the usefulness of HRV as an indicator of mental workload, unless variability caused by respiration can be eliminated. More complex analyses of HRV, such as power spectrum analysis, are beyond the scope of this study but may improve the information derived from the heart rate data (e.g. examining particular frequency ranges).

The NASA-TLX was used to assess mental workload and scores were found to be sensitive to changes in mental workload levels, as has been shown in previous studies (e.g. Alm and Nilsson, 1995; Hill et al., 1992). Increases in mental demands, requiring more resources, resulted in higher mental workload assessments. There was also an increasing trend associated with heavier loads. An increase in NASA-TLX scores was expected with increases in physical workload, due to the physical demand dimension included in the calculation of the overall assessment value (Colle and Reid, 1998).

Multidimensional rating techniques, such as the NASA-TLX, rely on a series of inferences in which the weight and value that an individual assigns to each piece of information is based on their existing knowledge base. A number of assumptions were made prior to the development of the NASA-TLX. One assumption was that by combining component judgments according to each individual's own inference rules (as reflected in the workload weights), an estimate of workload could be derived that would reduce some sources of between-subject variability that are irrelevant (Hart and Staveland, 1988). In the present results, however, scores calculated without weighting the dimensions were not significantly different from the original scores. Moroney (1995; 1992) determined mental workload during a simulated flight task and also found no significant difference between weighted and unweighted NASA-TLX scores. The weighting process within the NASA-TLX thus does not appear to substantially influence the sensitivity of the assessment tool so removal should be considered.

Only tasks requiring substantial mental activity and minimal physical activity were used to develop the NASA-TLX (Hart and Staveland, 1988). In order to assess the impact of the physical demand dimension, NASA-TLX scores were recalculated here without accounting for this rating. The overall scores were not significantly different and were similarly affected by the changes in mental and physical demands. This adjusted NASA-TLX rating was expected to more closely reflect the subjective assessment of mental workload, but the other dimensions were still influenced by the physical demand of the task. For example, assessment of physical demands was reflected in the effort dimension. Although originally intended as a mental workload assessment tool, during multi-task situations requiring substantial physical activity the NASA-TLX more closely reflects overall workload.

The VA Scale was sensitive to changes in mental workload levels. VA ratings increased with the difficulty of the arithmetic operations, and within each mental workload level the VA ratings differed with the required physical demands. Increases across the conditions were not constant, but discrepancies may have been due to the variations in the random numbers generated for the arithmetic problems. Increases in physical demands elevated VA ratings of mental workload, yet these ratings should not have been altered. The introduction of a concurrent physical task seemed to alter to

perceptions of mental workload, compromising the usefulness of this scale during multi-task situations.

Subjective mental workload assessments were sensitive to changes in required mental demands and can be used to compare difficulty levels of a mental task. Mental workload ratings using the NASA-TLX and VA Scale in multi-task situations, however, cannot be accurately compared to ratings associated with other tasks, since the mental workload ratings are affected by the physical component, reducing diagnosticity.

3.5.2. Assessment of physical workload

Normalized heart rate was used as an objective measure of physical workload. It was sensitive to changes in physical demands, as it significantly increased corresponding to increases in physical demand. This supported evidence that heart rate measures are acceptable indicators of physical intensity levels of a task (e.g. Johansson and Borg, 1993; Louhevaara, 1995). As with heart rate variability, the mental workload level did not substantially affect heart rate. Normalized heart rate appeared to provide a sensitive indication of physical workload that was not substantially affected by the addition of a predominantly mental task.

Distinct Borg CR10 ratings were given for the various physical workload levels, indicating the sensitivity of the scale and human perceptions of changes in physical workload. The sensitivity of the scale within this study confirmed previous findings that ratings increased with additional physical demands (e.g. Borg et al., 1987; Marks et al., 1983; Neely et al., 1992; Noble et al., 1983; Oberg, Sandsjo, and Kadefors, 1994). Average ratings for the low, medium and high physical workload levels corresponded to light, moderate and heavy ratings on the scale. Similarly, Genaidy et al. (1998) studied tasks performed in the package delivery industry and found perceived exertions to correspond to several levels of load heaviness. An overall trend in ratings of perceived exertions showed that the sensitivity of the Borg CR10 Scale to differing levels of physical demands was not altered with the introduction of a mental task.

The format of the physical demand dimension of the NASA-TLX is similar to the Borg CR10 scale. One major distinction is that the physical demand dimension is rated on a continuous scale, anchored by bipolar endpoints (low and high), whereas the Borg

CR10 scale requires numeric ratings associated with multiple anchor terms. Despite the differences in the structure of the scales, the physical demand dimension provided an overall rating of perceived physical workload that was approximately the same as the Borg CR10 ratings ($r = 0.80$), multiplied by a factor of 10. Moreover, the sensitivity of the physical demand dimension to mental and physical workload was analogous to the Borg CR10 Scale.

3.5.3. Subjective assessment of overall workload

Overall VA Scale ratings were sensitive to changes in physical demands and ratings provided at each physical workload level were significantly different from each other. Ratings were less sensitive to changes in mental demands. As with the mental VA Scale, there was no significant difference between the medium (subtraction) and high (multiplication) mental workloads. Higher ratings were expected with increases in physical and mental demands. Ratings for conditions requiring moderate to high mental and physical demands did not follow this trend, indicating that perceptions of workload levels were less clearly differentiated when individuals were asked to combine assessments of physical and mental demands during higher workload conditions. Participants seemed to have trouble interpreting the meaning of overall workload and consistently weighting the physical and mental workload components of the task. At higher workload levels, participants were required to reallocate resources that had previously been adequate to successfully perform both the mental and physical components of the task (Kahneman, 1973). Perceptions of physical workload were weighted more heavily than those of mental workload, and greatly influenced the overall workload assessments at higher physical workload levels.

3.5.4. Performance measures

It was evident that the mathematical operations differed in difficulty. The number of correct arithmetic responses for the addition problems was substantially higher than that of the other two operations. As suspected, multiplication was the most difficult, shown by the smallest number of correct arithmetic responses. The introduction of a physical load reduced the number of correct responses, with performance generally degrading further as the physical demands were increased. The addition of a physical

task seemed to impede performance of the arithmetic operations regardless of the difficulty of the mental activity. These results were similar to those of Paas et al. (1991) and Reilly and Smith (1984), albeit using different physical and mental activities.

The physical task was not completely automatic, because the pace was predetermined and resources were required to place the boxes in the appropriate target areas. As the load lifted was increased, more resources were required to properly perform the task. None of the mental workload levels requiring arithmetic were automatic. Arithmetic tasks are actually complex since recall, rehearsal and cognitive processes to complete the operation are required (Kahneman, 1973).

Individuals were able to complete both tasks concurrently. Kahneman (1973) described an undifferentiated pool of resources that would be allocated as necessary in multi-task environments. Performing a physical task while completing mental arithmetic problems required allocation of attention. The allocation policy was adjusted depending on the level of demands required and the individual performing the tasks. As hypothesized by Kahneman (1973), when the activities required exceeded the limits of attention for that individual, performance degraded. Experimental instructions dictated adherence to performance of the physical task (i.e. frequency of lifts and box placement), thus performance on the arithmetic task degraded as reflected in a reduction of the number of correct arithmetic responses.

3.5.5. Correlations between subjective and objective measures

The correlations between the subjective mental assessment tools and HRV did not provide beneficial information since HRV did not adequately respond to the differing levels of mental workload. Correlations between subjective assessment scores obtained using the NASA-TLX and performance (correct responses), although statistically significant, were weak and provided minimal practical information. Individuals rated mental workload as higher during conditions that degraded their performance on the mental arithmetic. Similarly, the performance dimension ratings within the NASA-TLX were significantly correlated to the number of correct responses. Correlations between the subjective VA mental workload assessment scores and performance were not significantly correlated, but an increasing trend in VA Scale ratings was associated with

the number of correct arithmetic responses. The number of correct responses was reduced as the difficulty of the mental task increased, but subjective mental workload assessments did not adequately reflect this change. Individuals were either unaware of the decrease in performance, or mental workload remained constant because the presentation speed of the mental problems was reduced. Regardless of the reason, subjective assessments of mental workload should not be evaluated to provide accurate estimates of performance.

Perceived exertions obtained using the Borg CR10 Scale were highly correlated with NHR. This result was expected since Borg (1973) created his physical exertion scales based on changes in heart rate. Further evidence has substantiated the relationship between perceived exertion and heart rate (e.g. Borg, 1977; Borg and Ottoson, 1986; Marks et al., 1983; Pandolf, 1983). More recently, research has used this relationship to investigate physical requirements of various tasks (e.g. Capodaglio and Bazzini, 1996; Hassmen, Stahl, and Borg, 1993). In the present study, Borg CR10 ratings represented actual physical demand levels with moderate accuracy and provided sensitive physical workload assessments.

Subjective ratings of overall workload were also strongly correlated with NHR. Interpretation of this result was difficult given the uncertainty of the relationship between mental workload and heart rate variability. Increases in overall workload ratings indicated a substantial influence of physiological reactions on the perception of workload, regardless of the reason for the reaction (e.g. physical activity, mental activity, stress). A verified objective measure of overall workload has not been established. Mital and Goviadaraju (1999) proposed myocardial oxygen consumption as an indicator of overall workload, but evidence to support this idea does not presently exist. Although the current results indicated that the overall VA Scale did not adequately reflect overall workload levels, substantiation of alternative assessment techniques requires the establishment of an accurate and sensitive objective measure.

3.5.6. Limitations

The participants used within this study were young adults; consequently, the results may not generalize to all adults. The activities used to produce mental and

physical workload were representative of a subset of those performed within many working environments. Further research is needed to verify these results for other types of mental and physical activity.

Objective measures of workload were obtained from heart rate data. Difficulties with the heart rate collection system may have compromised the accuracy of the relevant measures, making interpretation of the magnitude of workload problematic. Alternative methods of data collection and measurements of heart rate variability are recommended.

Subjective assessment tools were presented in the same order to all participants following the completion of a trial. The possibility of a carryover effect was not investigated. Subjective ratings may have been affected by this presentation order.

3.6. Conclusions

Multi-task situations required diverse levels of attentional resources to achieve a desired level of performance. Workload assessments were not dependent on the types of tasks performed, since the tasks were structurally dissimilar. Increases in physical or mental demands caused reallocation of resources and the degradation of performance as described in Kahneman's Capacity Model (Kahneman, 1973). Performance of the mental task degraded because the demands of the combined tasks were beyond the capacity of the individual and the experimental instructions dictated allocation of sufficient resources to be channeled into the physical activity to maintain a particular level of performance. Workload was determined given the resources available to the individual during each condition.

Subjective workload assessment techniques are used extensively within the research and occupational communities. The utility of existing subjective assessment tools created for one domain appear to be limited when evaluating multi-task situations requiring substantial mental and physical activity. In general, the VA Scale for mental workload and NASA-TLX were sensitive to changes in mental demands, but the magnitude of the rating or score was influenced by physical demands and, therefore, not necessarily indicative of actual mental workload levels. Subjective physical assessment tools (e.g. Borg CR10 Scale) may be used to assess physical workload during multi-task situations without being substantially influenced by the concurrent mental activity. The

VA Scale for overall workload should be used with caution, particularly when evaluating tasks requiring moderate to high physical or mental demands. Development of new subjective assessment techniques specifically designed for composite tasks is recommended to assess overall workload and mental workload during multi-task situations.

4. THE IMPACT OF DIFFERENT DIMENSIONS OF PHYSICAL WORKLOAD ON MENTAL WORKLOAD ASSESSMENT

4.1. Methods and Materials

4.1.1. Overview

Physical and mental workload can be approximated separately, but the specific effects of physical workload on mental workload assessment and performance have yet to be determined. More specifically, it has not been shown that existing assessment tools can be used to reliably estimate overall workload for situations involving both physical and mental demands. The lack of assessment tools for measuring combined physical and mental workload can partially be attributed to inconclusive studies and understanding of the relationship between physical demands and cognitive performance. The previous study examined the effects that changes in physical and mental demands have on subjective assessment of physical and mental workload. The present study was conducted in order to investigate how different types (or dimensions) of physical workload affect subjective mental workload assessment and performance. Critical dimensions were considered those aspects of physical workload that cause the greatest changes in an individual's mental workload assessment or performance.

During the design and evaluation of systems it is important to control factors that may increase the difficulty of tasks. Aspects of physical activity that impair mental workload assessment or decrease performance should be avoided when tasks require considerable levels of both physical and mental activity. Furthermore, the effectiveness of current subjective assessment tools during tasks involving both physical and mental activity is uncertain.

4.1.2. Experimental Goal

This experiment investigated the effect of several activity types, specifically global versus localized effort, changes in load, and different task frequencies on the subjective assessment of constant mental workload. Arithmetic tasks were used to impose mental workload. The goal of this research was to:

Determine the effects of different types of physical activity on mental workload assessment and performance.

4.1.3. Experimental Design

The experiment was a full factorial repeated measures design. Three independent variables were manipulated and three classes of dependent measures recorded. Type of effort, frequency, and load were the independent variables. Participants performed tasks in 18 separate conditions.

Each condition combined a physical and mental task, lasting for four minutes, with 2-minute rest periods provided between conditions. Participants were asked to assess mental workload using two subjective assessment techniques, specifically the NASA-TLX and a Visual Analog Scale. Perceptions of physical workload were assessed using the Borg CR10 Scale. Workload levels were also monitored using objective measures, specifically heart rate and heart rate variability.

4.1.4. Independent Variables

4.1.4.1. *Type of Effort*

Participants performed three types of physical effort. These efforts were intended to represent fundamental movements performed by individuals during a typical day of work. The types of effort were divided into localized (upper or lower limbs) and global (whole body). The first and second activity isolated either an arm or a leg, using elbow flexion and knee extension. Movements were performed on a commercial strength testing device (Biodex System 3 Pro, Biodex Medical Systems, Inc., Shirley, NY) with appropriate resistance being provided by the machine. The third activity involved the whole body and entailed climbing up and down a set of three stairs while carrying a load. These activities allowed for investigation of the impact of local (Activity 1 and 2) and central factors (Activity 3) on mental workload assessment.

4.1.4.2. *Frequency*

The frequency of movements was controlled at two levels (low, high). Low frequency was set at one extension or flexion per 10 seconds for the arm and leg, and one

pass up and down the stairs per 30 seconds for the stair climbing. High frequency required one extension or flexion every 5 seconds for the arm and leg, and one pass up and down the stairs every 12 seconds for the stair climbing. These frequencies were chosen to allow for relatively continuous movement with small breaks, encompassing a range of situations that would be encountered during a workday. It was emphasized to the participants that maintaining the pace set by the computerized auditory tones was required.

4.1.4.3. *Load*

Individuals performed the physical tasks at three intensity levels (Table 6), which were normalized to account for individual differences in strength and allow for inter-individual comparisons. Resistance was applied to the arms and legs using the Biodex System 3 Pro, and set at fixed percentages of individual strength for elbow flexion and knee extension. Strength was determined as the peak moment produced during an isokinetic movement controlled at the same angular velocity as the experimental conditions. The loads for the stair climbing conditions were determined as percentages of the individual’s body weight.

Table 6. Physical tasks representing the different workload levels. Loads were a percentage of strength or body weight for arm/leg movements and stair climbing, respectively.

Workload	Activity Level
Low	8%
Medium	14%
High	20%

In a pilot study (Section 4.2.1), the three levels of load were determined to be distinct by the participants’ subjective assessment of the difficulty of the tasks, although actual workload levels or effort required varied depending on the abilities of the participants. In particular, the task with the most weight or resistance was not proposed

as a maximum workload level; rather, it was ‘relatively’ high in relation to the other tasks.

4.1.4.4. *Mental activity*

In addition to the physical activity, the individuals concurrently performed an arithmetic task. This task was performed verbally so as not to interfere with the physical tasks. The difficulty level of the arithmetic task was kept constant, requiring moderate mental demands to perform the operation and rehearsal within short term memory (Kahneman, 1973). Participants were asked to subtract two numbers that were between 21-99, selected from a numeric list obtained using a random number generator. All subsequent lists (80 pairs of numbers) contained the same pairs of numbers in random order (examples of the numbers are in Appendix C). Participants completed a subset of the list during each condition (approximately 25 problems) so repetition of problems was limited. Participants commented that some of the problems were recognized but not remembered by the end of the experimental session..

4.1.5. Dependent Variables

4.1.5.1. *Performance Measure*

Performance of the mental task was determined as the number of correct responses provided in each condition. This metric was described in Section 3.1.5.1.

4.1.5.2. *Subjective Measures of Workload*

Perceived mental workload was assessed using a VA Scale and the NASA-TLX. The VA Scale recorded the participant’s overall assessment of mental workload performed during a task (see Section 2). The NASA-TLX (see Section 2) provided an assessment of mental workload based on a number of workload dimensions (Hart and Staveland, 1988; Miyake, 2001; Moroney et al., 1995). The purpose of and instructions for the assessment tools were carefully explained to the participant prior to the execution of the experimental conditions. The NASA-TLX was chosen because it is a widely used subjective mental workload assessment technique and it is easy to administer and

evaluate. The VA Scale was included because of its simplicity in determining an overall mental workload assessment score.

Subjective assessments of physical workload (or perceived exertion) were obtained by using the Borg CR10 Scale. The Borg CR10 Scale is commonly used as an assessment tool for whole body exertions (Borg, 1978; Borg, 1990; Borg and Noble, 1974; Noble et al., 1983; Robertson et al., 1998).

4.1.5.3. *Objective Measures*

Objective workload estimations were determined using heart rate and heart rate variability, obtained using a Polar S810 Heart Rate Monitor. Further details are in Section 3.1.5.3.

4.1.6. Participants

Thirty volunteers, between 18 and 24 years of age, were selected from the university community as described in Section 3.1.5.4, where the power analysis indicated that 30 participants was sufficient. Mean (sd) age of the participants was 20.2 (1.65) years. The mean (sd) body mass of the participants, used to determine the loads carried during the whole body exertions, was 71.2 (14.6) kg.

4.1.7. Apparatus and Materials

The experimental environment included two work areas, a staircase and the Biodex System 3 machine. The staircase had two sets of three stairs facing each other. The height of each stair was 172 mm (7") while the depth of each stair was 270 mm (11"), following architectural standards for indoor stairs (Hoke Jr., 1988). Wooden boxes were used to carry the loads during the stair climbing conditions, with the appropriate mass being achieved by adjusting the weights placed in the box. The width (the distance between the hands) of the boxes was 600 mm, while the depth (the distance away from the body) of the boxes was 340 mm. Cut outs in the lateral faces served as handles.

Heart rates were recorded and interbeat intervals measured using a Polar S810 Heart Rate monitor. The monitor consisted of two pieces of equipment, the chest strap and the wrist receiver. Interbeat intervals were reported in milliseconds.

4.1.8. Experimental Procedures

At the onset of the experiment, participants received information concerning the purpose, methods, and intent of the experimental procedures. All questions pertaining to the study were answered, and then participants were asked to read and sign an informed consent approved by the Virginia Polytechnic Institute and State University IRB.

Following completion of the informed consent, participants were verbally presented with 10 sample subtraction problems comparable to those used within the study, determined using a random number generator (Appendix D). Five minutes were provided to complete the list. Subsequent pairs of numbers were not presented until each problem was answered correctly. Participants were instructed to perform the arithmetic tasks as quickly as possible while minimizing errors. This preliminary set of tasks served as a screening tool; participants unable to complete the task were not allowed to continue with the experimental procedures. Learning or practice effects within the experiment due to lack of familiarity with performing mental arithmetic was reduced by providing participants an additional opportunity to familiarize themselves with the mental tasks by completing additional problems presented as in the screening tool.

The PolarTM S810 Heart Rate Monitor was placed on the participant's torso against the skin and the receiver (watch) on the wrist. Heart rate was then recorded for five minutes while a seated position was maintained. Resting heart rate was the minimum heart rate, averaged over 15 second intervals, obtained during this five minute period.

Instructions were provided for the scales that were used for subjective workload assessment (NASA-TLX and VA Scale). Prior to data collection, each participant performed maximum voluntary exertions (MVEs) in elbow flexion (45 deg/sec) and knee extension (30 deg/sec) using the Biodex System 3. Angular velocities were predetermined to simulate a natural movement speed. MVEs were isokinetic movements maintained at the same angular velocity as the experimental conditions. The largest moment produced from three repetitions was considered the maximum. Resistance loads during experimental trials were calculated as percentages of the maximum levels obtained.

Participants performed each of the conditions for four minutes while their heart rate was recorded. The duration of conditions was determined in a pilot study as sufficient to achieve steady state in heart rate (see Section 4.2.2). To prevent any confounding influences related to ordering (e.g., learning), the presentation order of the conditions was counterbalanced. Arm exertions required active flexion of the elbow throughout the full range of motion using the dominant arm. Leg exertions required active extension of the leg throughout the full range of motion using the dominant leg. The whole body exertions required lifting the load from the floor and carrying it while walking up and down the staircase.

Concurrent with the physical activity, numbers were recited that the participant subtracted. As participants performed the operation, they said their answer, with the same problem repeated until a correct response was given. The next set of numbers was provided immediately following a correct response, and mental activity continued until the end of the condition. The number of arithmetic tasks completed correctly was recorded. Although the physical task was not proposed as being more important than the arithmetic task, it was emphasized that maintaining the pace of the physical task was required but no time limit was set for completion of the arithmetic problems.

At the conclusion of each condition, a rest period of at least two minutes was provided, which minimized cumulative physical fatigue. During this time the subjective workload assessment tools (NASA-TLX , VA Scale and Borg CR10 Scale) were administered. The entire experiment took approximately 3 hours per participant.

4.2. Pilot Results

Two pilot studies were performed to address questions that arose during initial design. After the development of the physical tasks, it was necessary to determine levels that were perceived as three distinct loads. Subsequent to the formation of the activities to be performed, the duration of the trials also needed to be determined. This section describes the pilot studies and the conclusions drawn from the data obtained.

4.2.1. Levels of Physical Load

A pilot study was performed to determine three distinct resistance levels for the local workload conditions (arm and leg). The intention was to determine light resistance

levels that could still be perceived as different. Resistance provided by the Biodex was minimized in order to reduce the risk of injury to the participants and physical fatigue. Similarities between the carrying task in this study and the previous study (see Section 2.3.1.2) are substantial; therefore, identical percentages of body weight were expected to be characterized as distinct workload levels (see Section 2.7).

Four participants, two males and two females, performed the elbow flexion and knee extension tasks previously described at each load condition (low, medium, high) for five minutes. The resistance levels chosen were 8%, 14%, and 20% of the participant's MVE. No mental activity was performed. Borg CR10 ratings were collected at 30 second intervals and then averaged within each condition (Figure 25) to determine the subjective assessment values for each load. An ANOVA ($\alpha = 0.05$) indicated statistically significant differences in the CR10 ratings among the three conditions of each task. Post hoc comparisons of the means of the three groups within each task, using the Tukey-Kramer HSD ($\alpha = 0.05$), confirmed that the three resistance levels were assessed as distinct workload levels.

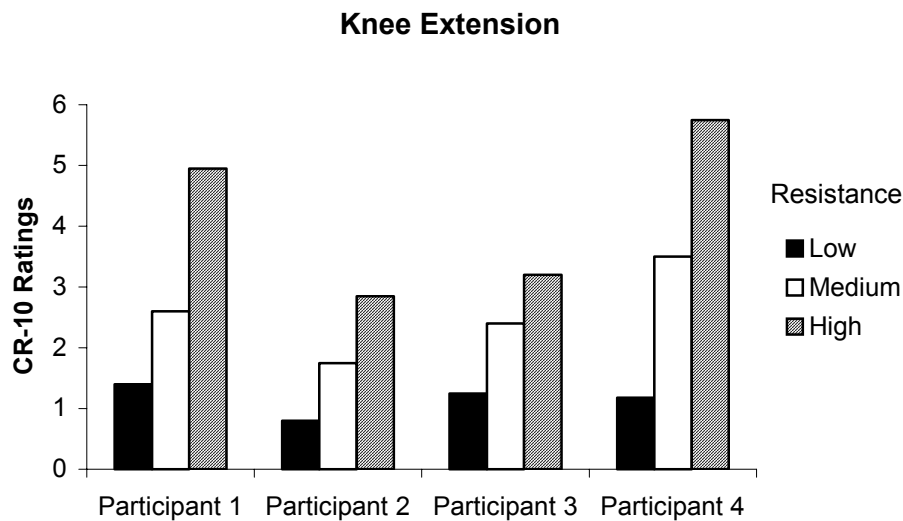
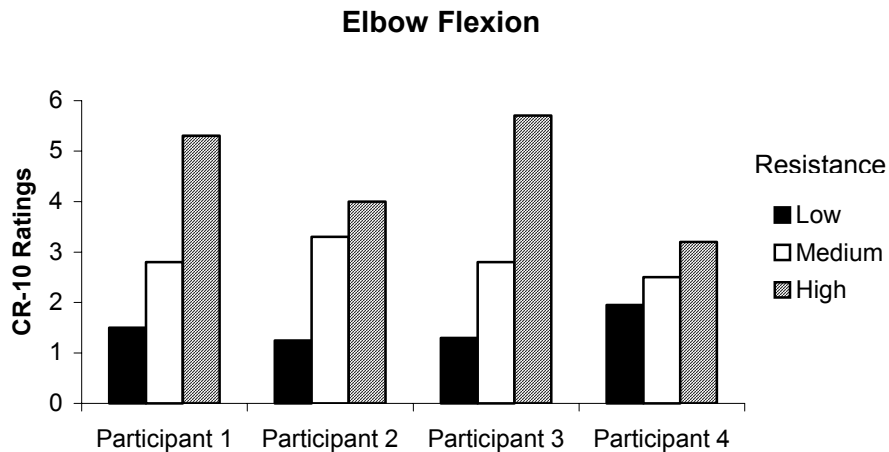


Figure 25. CR10 Ratings, from the pilot study, for the arm and leg conditions at each of the three resistance levels (low, medium, high).

4.2.2. Duration of Trials

The initial duration of the conditions was set at five minutes, but was found to lead to moderate-high levels of reported fatigue. A pilot study was conducted to determine if the duration of each condition could be reduced without compromising the accuracy of the data collected. Specifically, the intent was to determine the duration required for heart rate to achieve steady state in response to the physical task demands.

Four participants, two males and two females, performed the arm, leg and stair conditions at the lowest load levels and frequency for five minutes while their heart rates were monitored. These conditions were chosen because it would take longer for a steady state heart rate to be obtained as compared with the other conditions. Therefore, changes to the procedures involving these conditions would be applicable to the other conditions. The three conditions were completed without any mental activity, in order to minimize variability in the data due to factors not attributed to physical activity. The heart rate values were normalized, using the participant's maximum and minimum (resting) heart rates, and plotted versus time for each of the conditions (Figure 26).

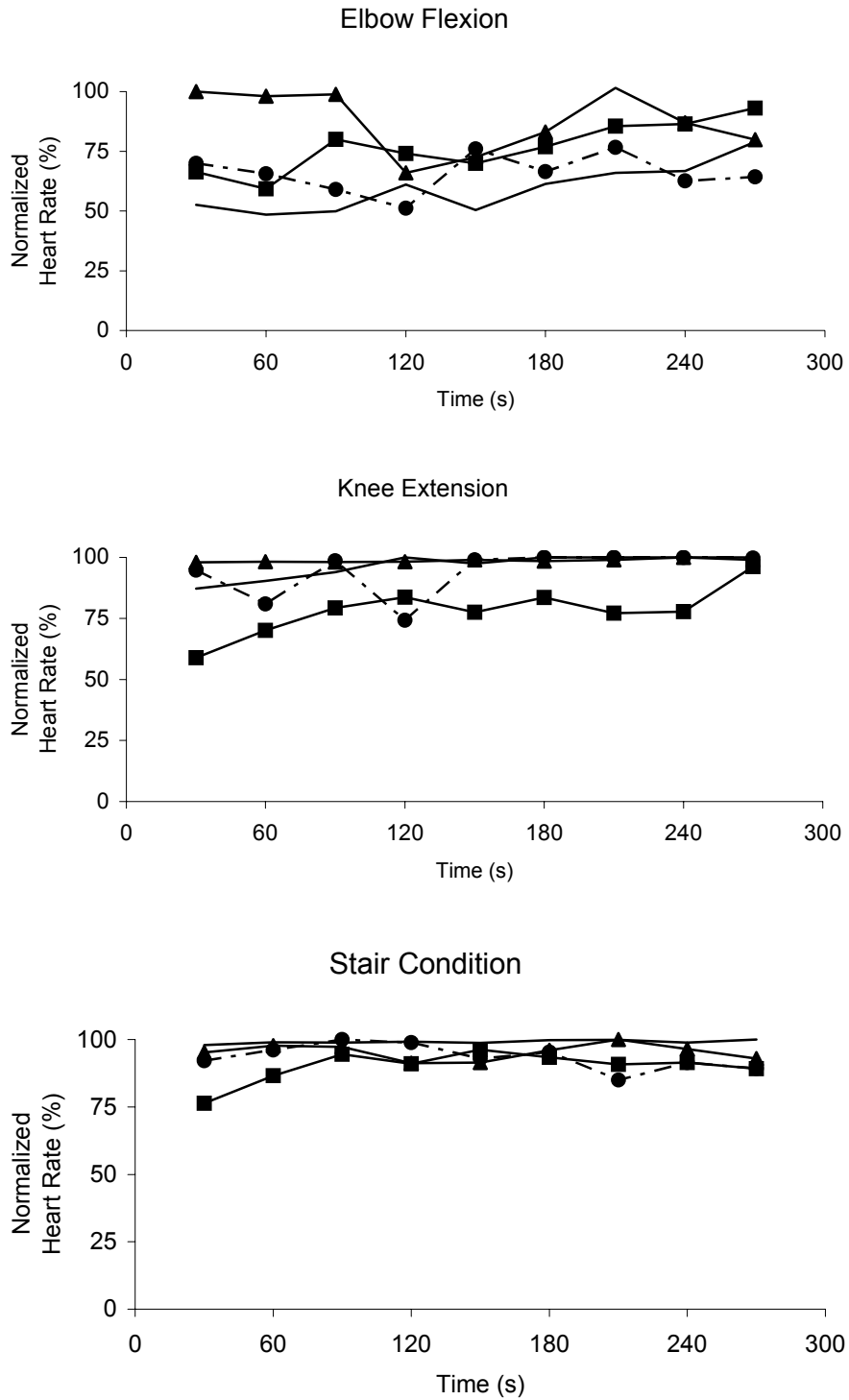


Figure 26. Normalized heart rate, from the pilot study, for each of the three physical tasks at the low frequency and load. Each line corresponds to a different participant.

The heart rate values for the four participants were averaged over 30 second intervals. The Tukey-Kramer HSD ($\alpha = 0.05$) was used to compare the means of the groups and determine when the heart rates stabilized. For each of the conditions, no significant differences were found between any of the intervals, signifying that heart rate remained constant throughout the condition. Based on these results and inspection of the data trends (Figure 26), trial durations of four minutes were deemed sufficient. Heart rate values were determined from the last minute of data collected.

4.3. Data Analysis

Data consisted of workload levels obtained from the NASA-TLX, VA Scale, Borg CR10 Scale, heart rate, and correct responses. Distributions of dependent measures were tested for normality, as described in Section 3.3, with no substantial deviations observed. Univariate repeated measures analyses of variance (ANOVA) were performed to evaluate the effects of type of effort, frequency and load on subjective mental workload assessment and performance, including significant interactions. Post hoc analyses, by means of Tukey-Kramer HSD test, were used to determine which changes (e.g. low to medium load) caused significant differences in subjective mental workload assessment and performance. Objective measures (heart rate and heart rate variability) were correlated with the subjective assessment values to determine the relationships between workload levels and subjective assessments. All statistical analyses were evaluated at a significance level of $\alpha = 0.05$.

4.4. Results

The results were divided into six categories: (1) effect of varying physical activity type, represented by global and localized effort, on mental workload assessment, (2) effect of varying the load during physical activity on mental workload assessment, (3) effect of varying the frequency of physical activity on mental workload assessment, (4) performance measure, (5) effect of interactions on mental workload assessment and performance, and (6) correlations between subjective and objective measures. Significant effects are identified and p-values reported only for nonsignificant factors.

4.4.1. Effect of varying physical activity type, represented by global and localized effort, on mental workload assessment

Subjective assessments of mental workload, determined using the VA Scale and NASA-TLX, were similar for all three activity types (Figure 27). The effect of activity type was significant on VA Scale ratings but not NASA-TLX scores ($p=0.36$). Post hoc analysis of the VA Scale ratings showed that ratings obtained during elbow flexion were significantly different from the other two activity types. Furthermore, scores were not significantly different for the VA Scale and NASA-TLX, although ratings from the VA Scale were consistently larger.

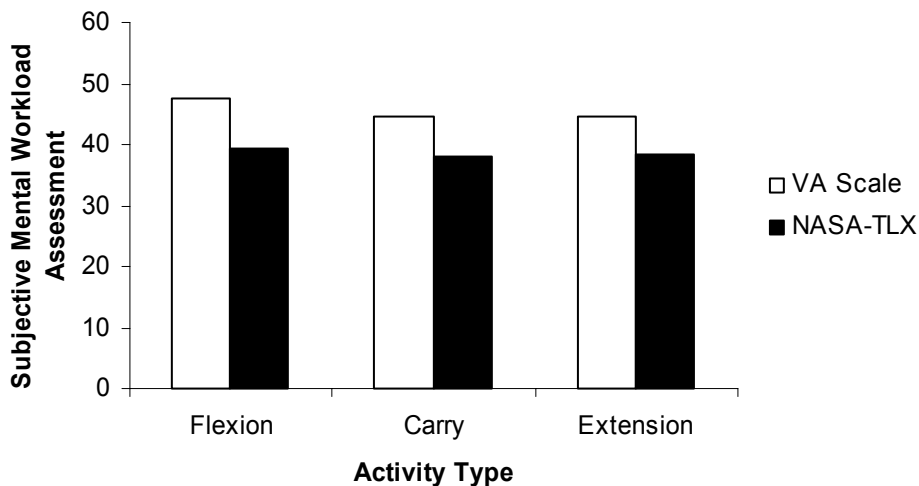


Figure 27. Mental workload assessment scores, using a VA Scale and NASA-TLX, for conditions of different activity type. Results are averaged across all levels of frequency and loads.

Mental workload was measured objectively using heart rate variability. The effect of activity type (Figure 28) was significant. HRV was similar during elbow flexion and whole body exertions, and both were significantly larger than values calculated during knee extension.

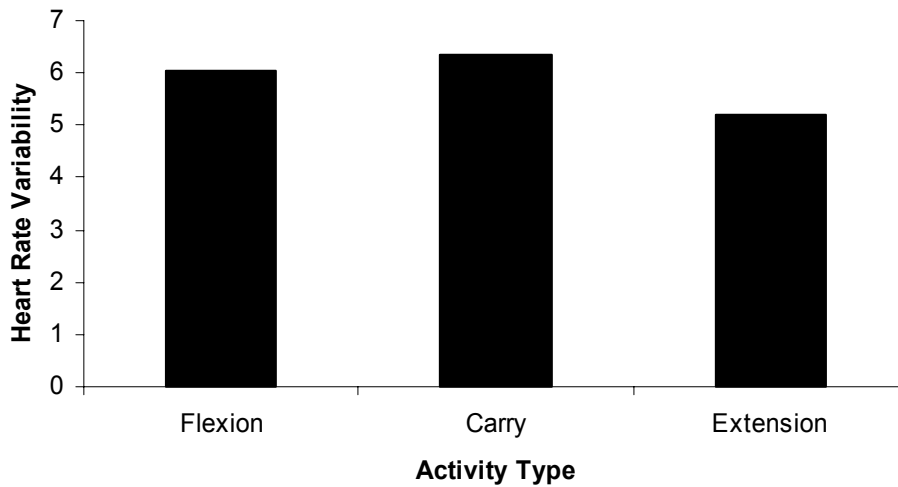


Figure 28. Objective measure of mental workload, as indicated by heart rate variability, for conditions of varying activity type.

4.4.2. Effect of varying the load during physical activity on mental workload assessment

Assessment scores obtained using the VA Scale and NASA-TLX were similar for the three load levels (Figure 29), although the VA Scale consistently produced larger scores. The effect of load was significant on VA Scale ratings but not NASA-TLX scores ($p=0.23$). Paired comparisons of the VA Scale ratings showed a significant difference in ratings for the low load conditions as compared to the higher levels, but no significant difference between the medium and high loads. In addition, load level did not cause a significant effect on HRV ($p=0.82$).

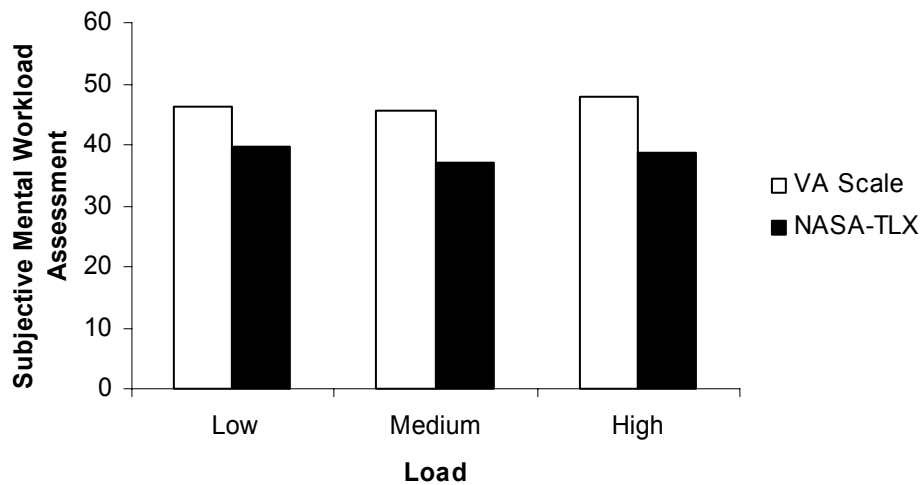


Figure 29. Mental workload assessment scores, using a VA Scale and NASA-TLX, for different load conditions. Results are averaged across all levels of activity type and frequency.

4.4.3. Effect of varying frequency during physical activity on mental workload assessment

Mental workload assessment scores, using the VA Scale, significantly increased with an increase in frequency (Figure 30). Frequency did not have a significant effect on NASA-TLX scores ($p=0.67$). Results obtained using the VA Scale were consistently higher than those of the NASA-TLX.

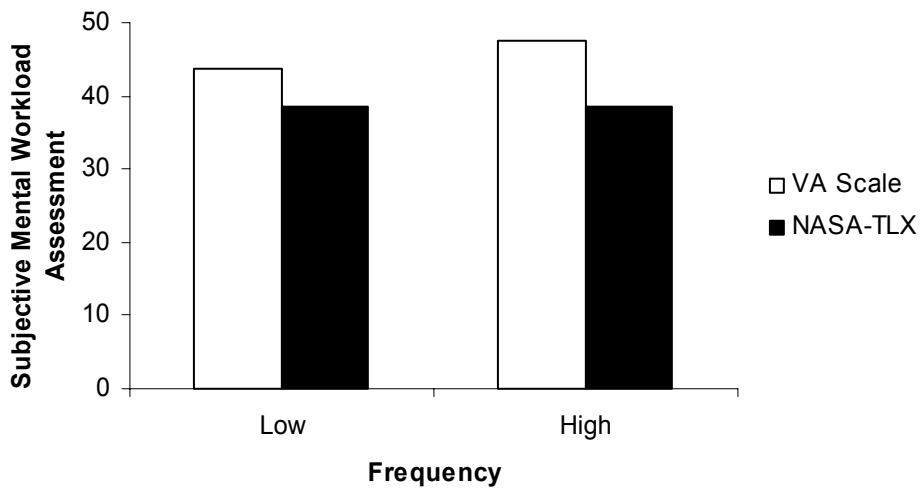


Figure 30. Mental workload assessment scores, using a VA Scale and NASA-TLX, for conditions of different frequency. Results are averaged across all levels of activity type and load.

A significant effect of frequency on HRV was found (Figure 31). HRV decreased with an increase in frequency.

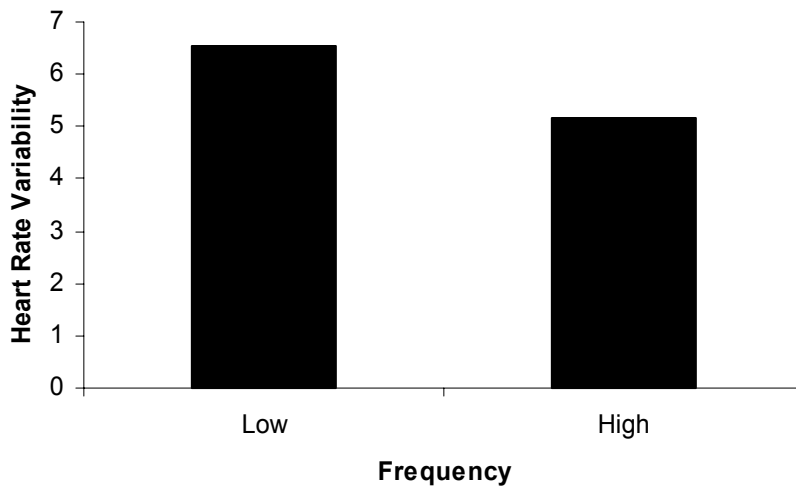


Figure 31. Objective measure of mental workload, as indicated by heart rate variability, for conditions of varying frequency.

4.4.4. Performance Measure

The effect of load on the number of correct responses was not significant ($p=0.11$). Performance was significantly affected by type of activity (Figure 32) and frequency (Figure 33). Elbow flexion and an increase in frequency reduced the number of problems answered correctly during each trial. Paired comparison of means indicated a significant difference in performance between the elbow flexion and knee extension conditions. Performance decreased during elbow flexion, but performance during the carry and knee extension conditions was significantly higher.

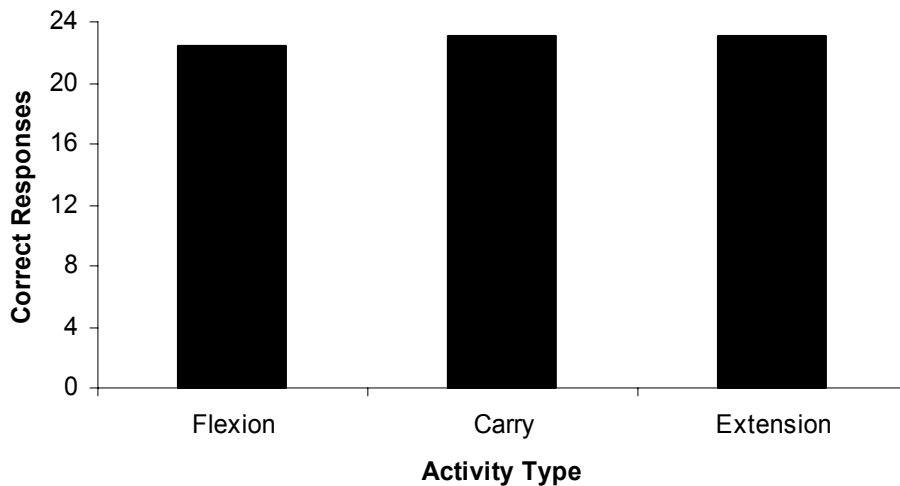


Figure 32. The number of correct arithmetic responses for three types of activity.

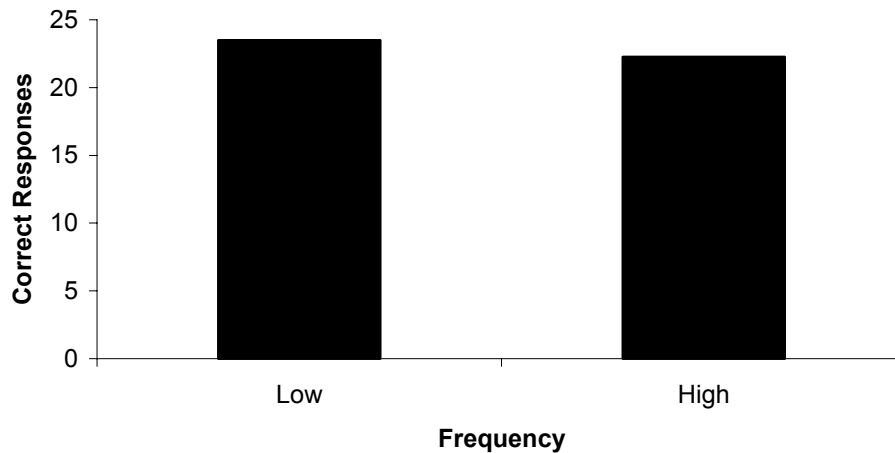


Figure 33. The number of correct arithmetic responses for two frequency levels.

4.4.5. Effect of interactions on mental workload assessment and performance

The effects of interactions between the three factors investigated were examined, with many being insignificant, including the three-way interaction. No interactions significantly affected subjective mental assessment values (VA Scale and NASA-TLX).

The effect of one interaction was significant on HRV. HRV was greatest for the carry conditions, with those of the local efforts being similar to each other. The difference in HRV between the low and high frequency was also significantly greater for the carry conditions and slightly larger during elbow flexion as compared to knee extensions (Figure 34).

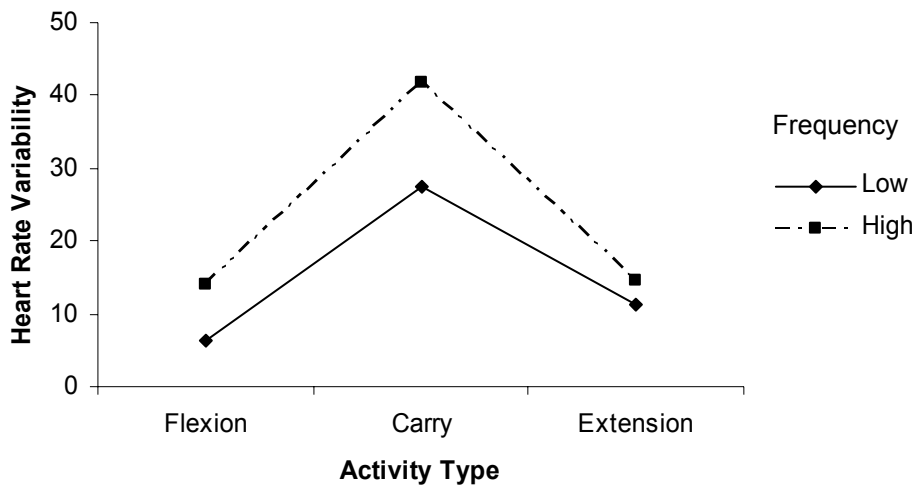


Figure 34. Heart rate variability for conditions of varying activity type and frequency. Both lines would ideally be parallel if no interaction existed.

4.4.6. Correlations between subjective and objective measures

Correlations (r) between the subjective and objective measures of mental workload were determined. HRV was not significantly correlated with the VA mental ratings ($p=0.74$) or the NASA-TLX scores ($p=0.08$) used to subjectively assess mental workload. Performance of the arithmetic task was significantly correlated with the VA Scale ratings ($r = -0.15$) and NASA-TLX scores ($r = -0.21$). The negative correlation indicates that as performance degraded, subjective mental workload assessment values increased.

NHR was significantly correlated with perceptions of physical workload, using subjective assessment ratings from the Borg CR10 Scale ($r = 0.14$). Performance was also significantly correlated with the Borg CR10 ratings ($r = -0.13$). Borg CR10 ratings increased with NHR, decreased when performance diminished.

4.5. Discussion

Comprehensive subjective assessments of overall workload include the evaluation of physical demands, mental demands, and also evaluate their interaction. This study examined the effect of several aspects of physical workload on subjective mental

workload assessment during tasks comprising both physical and mental activities. Particular characteristics of the physical activity were investigated to determine the critical dimensions as related to mental workload assessment and performance.

4.5.1. Effect of varying physical activity type, load, and frequency on mental workload assessment and performance

Activity type did not seem to significantly affect the participants' subjective assessment of mental workload. Although scores, determined by the VA Scale, were similar for knee extension and whole body exertions, those of elbow flexion were slightly larger. A slight, but nonsignificant, decrease in performance was associated with the elbow flexion condition, corresponding to the change in subjective workload assessment. Therefore, the VA Scale indicated a change in perception of mental workload when there was an effect on the arithmetic task, although individuals tended to perceive a disproportionate difference. The NASA-TLX was not sensitive to the changes in types of physical activity and did not reflect changes in performance, even though the scale included a performance dimension.

Subjective mental workload assessments obtained from the VA Scale were significantly different between the low and higher loads but did not reflect the significant change in performance between the medium and high load levels. NASA-TLX scores did not significantly change for any of the conditions. Scores were expected to be altered since the tool included a physical demand dimension and the physical load was being manipulated. Performance on the arithmetic tasks, however, corresponded to trends in the participants' assessments of mental workload.

VA Scale ratings were sensitive to the change in frequency of the physical tasks. The VA Scale ratings were consistently larger than those of the NASA-TLX and significantly changed with the increase in frequency, whereas the NASA-TLX scores were not significantly affected. Higher frequency did have a significant detrimental effect on performance of the arithmetic task, corresponding to the results obtained from the VA Scale. Even though the NASA-TLX included a temporal demand dimension, it was not sensitive to changes in frequency.

The execution of a concurrent physical task and mental task was altered by the magnitude of the physical demands within the condition. Increases in physical demands, regardless of source, caused decreases in performance on the mental arithmetic. Performing more physically demanding tasks required more resources, so less were available for completion of the arithmetic task, resulting in less correct arithmetic responses. Individuals perceived changes in mental workload with moderate accuracy, reflected in VA ratings, although the actual mental demands remained constant. Although the NASA-TLX has been a commonly used tool for measuring mental workload (e.g. Alm and Nilsson, 1995; Hill et al., 1992; Temple et al., 2000), scores obtained during multi-task situations were influenced by changes in physical demands, possibly diminishing its effectiveness in tasks with substantial mental and physical demands.

4.5.2. Effect of interactions on mental workload assessment

There was a significant interaction effect between activity type and frequency on HRV but not on performance or either of the subjective assessment measures. Within each activity type there was a substantial difference in assessments for the low and high frequencies. Frequency caused similar changes in HRV for both of the local efforts. The difference in HRV for the whole body exertions was significantly larger. HRV was expected to decrease with increases in mental workload (Meshkati, 1988). This result may be attributed to the significant change in heart rate that accompanied the greater aerobic demands (Sammer, 1998).

4.5.3. Correlations between subjective and objective measures

The objective measures of mental and physical workload were significantly affected by the independent variables. The mental demands remained constant throughout the experiment, but perceptions of mental workload were not constant. The objective and subjective measures were not significantly correlated. A portion of the discrepancy between the two measures may be due to the large changes in heart rate during some of the experiment conditions and the limitations of HRV as an indicator of mental workload (Nickel and Nachreiner, 2000).

Changes in physical dimensions caused alterations in NHR and Borg CR10 ratings as expected, based on previous research using both measures (e.g. Borg et al., 1987; Borg et al., 1985; Chung, Lee, and Yeo, 2001; Neely et al., 1992; Pfeiffer, Pivarnik, Womack, Reeves, and Malina, 2002). The two measures, however, were not significantly correlated, indicating incongruent objective (physiological) and subjective reactions to changes in physical workload. The low correlation was partially due to the intermittent nature of the physical tasks. Although not highly correlated, the changes in both measures confirm that the variations in physical dimensions significantly altered the level of physical workload.

Performance was an objective measure of mental capabilities given the physical dimensions of the task. VA Scale ratings were significantly correlated with the number of correct arithmetic responses. Individuals were able to perceive an increase in difficulty completing the arithmetic tasks due to changes in the physical demands. Furthermore, perception of the physical demands was altered, as indicated by a significant negative correlation between Borg CR10 ratings and performance.

4.5.4. Limitations

Limitations of the usefulness of the heart rate data were similar to the previous study. There were limitations in generalizability of the results caused by the homogeneous participant population and carryover effects might have influenced ratings during the administration of the subjective assessment tools. In addition, the localized efforts were highly controlled physical movements. Results should be verified for less automatic and constrained localized efforts.

4.6. Conclusions

Physical tasks are comprised of many different dimensions. Alterations in the different dimensions significantly affected the physical demands associated with the tasks. Evidence of changes was indicated in NHR analysis and perceptions of physical workload (Borg CR10 Scale).

The NASA-TLX was used to evaluate mental workload based on six dimensions, two of which were manipulated in this experiment. This scale was not sensitive, however, to changes in the physical dimensions. Based on the outcome of this study, the

NASA-TLX is not recommended as a workload assessment tool for tasks involving physical and mental demands. The VA Scale was sensitive to changes in all three physical dimensions. The variation in ratings corresponded to changes in performance on the mental task. Effects were dependent on the quantity and type of muscles required to perform the task, not the actual activity, substantiating the applicability of Kahneman's Capacity Model (Kahneman, 1973).

The results provide support that the type of activity, load and frequency of task influence subjective mental workload assessment scores and performance. Not all existing assessment tools accurately represent an individual's ability to perform a task when there is a combination of physical and mental demands. A unidimensional tool, such as the VA Scale, is suggested as a screening tool to identify situations requiring excessive or increased mental workload. Alternative methods, possibly a new multidimensional tool, should be developed to obtain more detailed and diagnostic information so ratings of workload for different tasks may be compared.

5. EFFECTS OF MENTAL WORKLOAD ON SUBJECTIVE ASSESSMENT OF POSTURAL STABILITY

5.1. Methods and Materials

5.1.1. Overview

Several objective measures of postural sway have been developed to quantify the movement required to maintain and control upright postures. Many occupations (e.g. construction workers, health care professionals) require individuals to maintain upright postures for extended periods of time while performing various concurrent tasks. Loss of balance while performing these tasks may result in a fall causing injury. Assessing and maintaining postural stability are two methods for reducing the frequency of such incidents.

Information from the visual, vestibular and somatosensory systems is used to maintain balance and postural stability (Mirka and Black, 1990; Winter, 1995). Changes in the information received from these systems affect postural sway and potentially the perception of steadiness. Input from the vestibular system is difficult to control, but altering visual cues and postural stances affects the information provided by the visual system and somatosensory system, respectively. Occupational activities are frequently performed with limited visual cues, while maintaining difficult postural stances, or concurrent with mental activity.

Maintaining an upright posture while completing mental tasks requires the allocation of attention and resources, with interactions and effects on postural sway dependent on the nature and complexity of the individual tasks (Dault et al., 2001b; Yardley et al., 2001). Effects on postural sway have been extensively investigated, however, subjective assessment of postural stability has received considerably less attention. It is not known if the cognitive processing required for mental activity affects an individual's perception of steadiness and if that effect is consistent across conditions of varying mental and physical difficulty.

There is an important need for methods to evaluate existing and new prevention strategies, and more generally to determine factors that lead to falls. Subjective ratings

can be used for task evaluation and monitoring of balance control creating minimal interference with the tasks being performed. Schieppati (1999) introduced a scale for the subjective assessment of postural stability and indicated that the subjective assessment ratings reflected changes in objective measures of postural sway (Section 2.6.2). In the present study, effectiveness of this subjective stability assessment tool (Schieppati et al., 1999) was evaluated quantitatively during laboratory-based experiments in situations demanding mental activity while maintaining an upright posture. Tests were performed over a wide range of conditions, including various mental loads, sensory conditions, and postural stances. The purpose was to determine the effects of each task variation on the perception of postural stability.

5.1.2. Experimental Goals

This experiment was formulated to evaluate the effects of task variations on the subjective assessment of postural stability. Postural stability was determined while an upright stance was maintained under a variety of sensory conditions, and concurrent arithmetic tasks were used to represent mental workload. The goals of this research were to:

1. Determine the effect of differing levels of mental activity on the objective and subjective assessment of postural stability.
2. Determine the effect of varying visual feedback on the objective and subjective assessment of postural stability.
3. Determine the effect of varying upright postural stances (foot placements) on the objective and subjective assessments of postural stability.

5.1.3. Experimental Design

The experiment was a full factorial repeated measures design. Three independent variables were manipulated and three classes of dependent measures recorded. Mental activity performed (three levels), visual condition (two levels), and postural stance (three levels) were the independent variables. Participants performed tasks in 24 separate conditions.

Each condition, comprising a mental task and sustained upright stance, lasted for one minute, with a rest period provided between conditions of at least one minute.

Carpenter et al. (2001) adjusted the methodology recommended by LeClair and Riach (1996) and determined that sampling durations of 60s are more stable and reliable than 30s for determining postural sway measures during quiet stance. Participants were asked to provide subjective mental workload and postural stability assessments, using a Visual Analog Scale (Section 2) and postural stability scale (Schieppati et al., 1999), respectively. These methods were selected because of their ease of use and application during previous experimental research. Moreover, the scale developed by Schieppati et al. (1999) is the only such scale presently proposed in the literature for obtaining subjective assessments of postural stability.

5.1.4. Independent Variables

5.1.4.1. *Mental Activity*

Addition and multiplication tasks (described in Section 3.1.4.1 and Table 3) were used to achieve three intensity levels (no load, low, high) of mental workload. This mental activity (arithmetic) was chosen since it required cognitive processes and was easy to implement without introducing a physical demand that might interfere with the measures of postural sway.

5.1.4.2. *Visual Condition*

Participants performed tasks under two types of visual conditions. These conditions were intended to alter the difficulty of the task and assist in determining the importance of visual cues to subjectively assess postural stability. The first condition required the participants to keep their eyes open and look at a target located at eye level and a distance of approximately 50cm (Schieppati et al., 1999; Tarantola, Nardone, Tacchini, and Schieppati, 1997). Participants were asked to close their eyes throughout the second condition to ensure the absence of visual cues.

Inputs from the visual system, in addition to the somatosensory and vestibular systems, are used to determine necessary postural adjustments. Objective postural sway measures have been shown to increase when visual cues are substantially altered or removed (e.g. Nardone, Tarantola, Giordano, and Schieppati, 1997; Tarantola et al.,

1997), but the effect of these variations on an individual's perception of postural stability has not been established.

5.1.4.3. *Postural Stance*

Three upright postural stances were used for the experimental conditions. All postural stances were performed while the participant was barefoot with arms at the side. Feet shoulder width apart and parallel were used to provide the base of support during the first stance. This stance was closest to a natural position (width of 0.17m) and provided a satisfactory base of support for maintaining balance (Dault et al., 2001a). Placing the feet together increased the difficulty of maintaining balance during the second stance (Tarantola et al., 1997). The most difficult stance was with the feet in a tandem heel-to-toe position (Romberg stance), with the participants choosing which foot to place in front.

Variations in postural stances and difficulty encompassed a range of situations that are encountered during a workday. Although objective changes in postural sway have been recorded for different postural stances, the impact on perception has yet to be established. Subjective assessments determined if changes in postural stance and associated challenges to the postural maintenance systems affected perceptions of postural stability.

5.1.5. Dependent Variables

5.1.5.1. *Subjective Measures*

Subjective mental workload was assessed using a VA Scale. The VA Scale recorded the participant's overall assessment of mental workload performed during a task (see Section 2). The VA Scale was included because of its simplicity in determining an overall mental workload assessment score.

Postural stability was subjectively assessed using a procedure developed by Schieppati et al. (1999). Individuals used a rating scale to indicate perceptions of postural stability. To use the scale, individuals provided a score in the range of 0 (worst) to 10 (best) that indicated how stable they felt while maintaining an upright stance during the condition. A response of 0 indicated that the individual did not feel stable at all while

a response of 10 indicated that the individual felt completely stable. Half points and quarter points were allowed to distinguish between trials producing small differences in postural stability.

5.1.5.2. *Objective Measures (Static Force Plate Measures)*

Postural sway was recorded using a force plate (Kistler-Bertec, 4550-08, Kistler Instrument Corp., Amherst, N.Y.). Information from the force plate consisted of triaxial forces and moments, which were sampled at 100 Hz, and low-pass filtered (second-order Butterworth: 10 Hz cutoff). The filtering frequency was determined based on earlier evidence that the signal content of postural sway is primarily at frequencies ≤ 5 Hz (Hufschmidt, Dichgans, Mauritz, and Huschmidt, 1980). Center-of-pressure locations in the plane of the force plate were determined using standard transformations (Winter, 1990), utilizing data contained in the 5th through 55th seconds to minimize effects of postural adjustments at the beginning and end of a trial (Derave, De Clercq, Bouckaert, and Pannier, 1998). Prior to calculating the postural sway measures, mean values were removed in the medio-lateral (ML) and antero-posterior (AP) directions.

Several COP-based measures of postural sway have been developed. In this study, five common COP-based measures were included (mean distance, RMS distance, mean velocity, peak velocity, sway area). Prieto et al. (1996) categorized the first four variables as time-domain distance measures, whereas the last variable, sway area, is a time-domain area measure. COP velocity was estimated using finite differences (Winter, 1990), and mean and peak velocity determined for the 50-second sub-sample. Sway area was calculated (Equation 7) as the region encompassed by the shift of the line joining the mean center of foot pressure to the moving center of foot pressure (Diener, Dichgans, Bacher, and Gompf, 1984). The Euclidean distance R was determined from the ML and AP components yielded by each of the COP measures. Equations listed below are those for R , simple substitution yielded the equations for the ML and AP components.

$$\text{Mean Distance} = (1/n) \sum R(n) \quad (4)$$

$$\text{RMS Distance} = \left[(1/n) \sum R(n)^2 \right]^{1/2} \quad (5)$$

$$\text{Velocity} = (R_{n+1} - R_{n-1}) / 2(\Delta t) \quad (6)$$

$$\text{Sway Area} = (1/2) \sum |AP(n+1)ML(n) - AP(n)ML(n+1)| \quad (7)$$

5.1.6. Participants

Thirty volunteers, between 18 and 24 years of age, were selected from the university community as described in Section 3.1.5.4, where the power analysis indicated that 30 participants would be sufficient. The mean (sd) age of the participants was 19.9 (1.4) years old.

5.1.7. Experimental Procedures

At the onset of the experiment, participants received verbal and written information concerning the purpose, methods, and intent of the experimental procedures using a standardized set of instructions. They were given an opportunity to ask any questions pertaining to the study, and then asked to read and sign an informed consent approved by the Virginia Polytechnic Institute and State University IRB.

Following completion of the informed consent, participants were verbally presented with 10 arithmetic problems from each difficulty level used within the study. A set of numbers was determined using a random number generator (Appendix B). Subsequent pairs of numbers were not presented until each problem was answered correctly. Participants were instructed to perform the arithmetic tasks as quickly as possible while minimizing errors. Five minutes were provided to complete each list. This preliminary set of tasks served as a screening tool; participants unable to complete the task were not allowed to continue with the experimental procedures.

Learning or practice effects within the experiment due to lack of familiarity with performing mental arithmetic was reduced by providing participants an additional opportunity to familiarize themselves with the mental tasks by completing additional

problems presented as in the screening tool. The purpose of and instructions for the assessment tools were carefully explained to the participant at the completion of the practice session and prior to the execution of the experimental conditions.

Instructions on the use of the postural stability scale included a calibration procedure described by Schieppati et al. (1999). Calibration was used to provide references for the individuals to facilitate understanding of the extreme values of the scale. Initially, individuals stood with feet shoulder width apart, eyes open and grasping a fixed object. At this time the individual was asked to consider this situation a '10', or completely stable. Individuals were then instructed to balance on one leg with eyes closed, a situation that most individuals cannot maintain for a substantial amount of time. This situation was considered an unstable condition and individuals were instructed to associate it with a very low score or even '0'.

Prior to the experimental conditions, the participant stood on the force platform in each of the postural stances with the experimenter outlining the position of the feet on a sheet of paper placed over the force platform. This was done to maintain uniformity between trials that required the same postural stance. During the experiment, participants performed each of the conditions for one minute while their postural sway was recorded. The presentation order of the conditions was counterbalanced to prevent any confounding influences related to ordering (e.g., learning).

When instructed to begin, the participant maintained the indicated postural stance with eyes open or closed as dictated by the condition. Concurrently, numbers were recited that the participant added, subtracted, or multiplied depending on the condition. Participants performed the operation and said their answer as quickly as possible. Each pair of numbers was repeated until a correct response was given, with the next set of numbers provided immediately following a correct response. Mental activity was continued throughout the condition. Participants were informed that conditions would be repeated if balance was not maintained for the entire condition. However, they were instructed that continuous mental effort to complete the arithmetic tasks was required. At the conclusion of each condition, the participant completed the two subjective workload assessment tools (VA Scale for Mental Workload and Postural Stability Scale). The entire experiment took approximately one hour per participant.

5.2. Data Analysis

The VA Scale, subjective postural stability scale, and objective postural sway measures generated the data regarding workload levels. Substantial deviations from normal were observed in the distributions of dependent measures. Normality was tested as described in Section 3.3. All dependent measures were normalized by means of a logarithmic transformation, which allowed for the use of parametric analyses. Univariate repeated measures analyses of variance (ANOVA) were performed to evaluate the effects of mental workload, visual cues, and postural stance on postural sway and subjective assessment of postural stability. The Tukey-Kramer HSD test was used to perform pairwise comparisons between the levels of the dependent variables. Correlations were determined between the multiple objective measures of postural sway and the subjective ratings of postural stability. Significance for all statistical analyses was determined at $p < 0.05$.

5.3. Results

Five categories were used to divide the results: (1) assessment of postural sway, (2) subjective assessment of postural stability, (3) subjective assessment of mental workload, (4) effect of interactions, and (5) correlations between subjective and objective measures. Table 7 summarizes the effects investigated within the study and the associated p-values.

Table 7. P-values for the main effects and interactions of mental workload, postural stance, and visual condition on measures of postural sway and postural stability.

	Mean Distance (MD)	Mean Velocity (MV)	Peak Velocity (PV)	Root Mean Square Distance (RMSD)	Sway Area (SA)	Postural Stability Rating (PSR)
Mental Workload (M)	<0.01	<0.01	0.72	<0.01	0.60	0.60
Postural Stance (P)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Visual Condition (V)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
M x P	0.62	0.86	0.52	0.57	0.94	0.33
M x V	0.96	0.37	0.62	0.95	0.88	0.54
P x V	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
M x P x V	0.14	0.61	0.70	0.24	0.31	0.66

**bold and italics* represents significance at $p \leq 0.05$

5.3.1. Assessment of postural sway

Objective measures of postural sway increased significantly with increases in difficulty of postural stance and during conditions without visual cues. Post-hoc paired comparisons found significant differences in objective postural sway measures between each postural stance. The change in postural stance had a greater impact on objective postural sway measures at higher difficulty levels. The medio-lateral and antero-posterior components of the objective measures were significantly affected by the same factors as the original measures. Therefore, no further analyses were performed on the components.

The effect of mental workload was not significant for peak velocity ($p=0.72$) and sway area ($p=0.60$). A significant effect was found on the other objective measures of postural sway (Figure 35). Mean distance and RMS distance decreased with increases in mental workload, however, no trend was found for the velocity measures. The distance measures significantly decreased with the introduction of the mental activity.

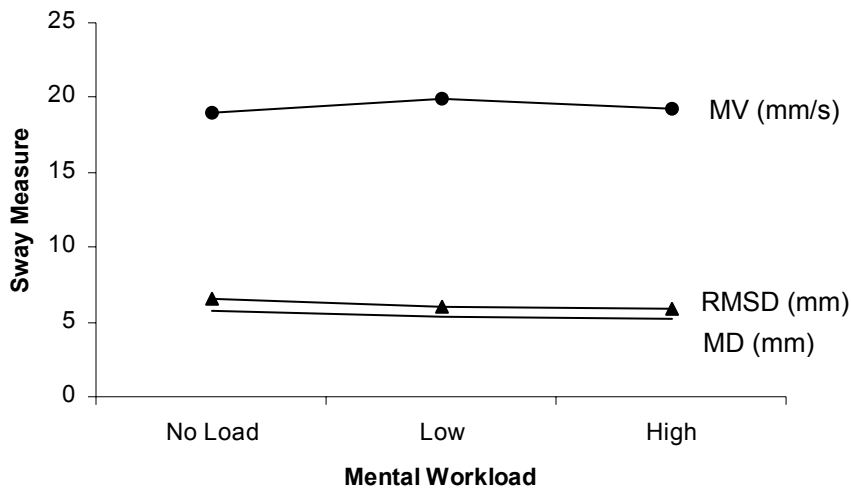


Figure 35. Changes in objective measures (MD – mean distance; MV – mean velocity; RMSD – RMS distance) of postural sway for each of the mental workload levels.

5.3.2. Subjective assessment of postural stability

Subjective assessment of postural stability, represented by postural stability ratings, decreased as the difficulty of the postural stances increased (Figure 36). The absence of visual cues also caused a reduction in postural stability assessments (Figure 37).

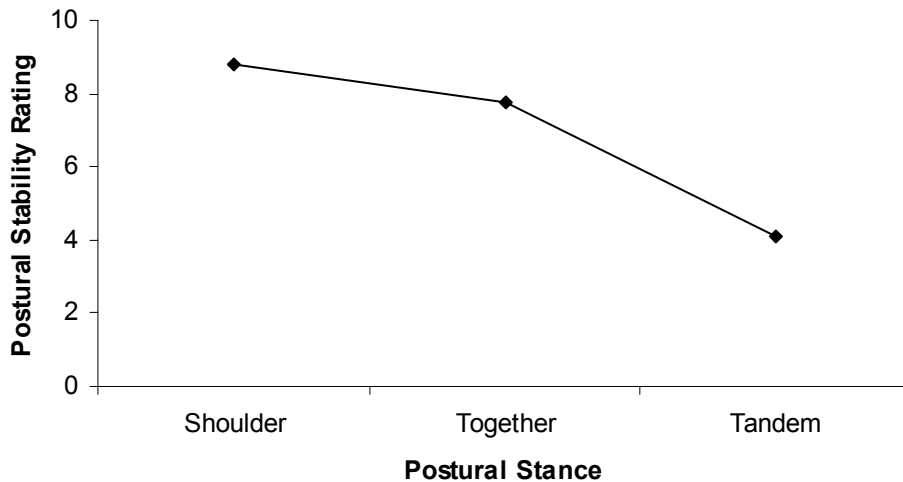


Figure 36. Postural stability ratings for varying postural stances. Postural stances were selected to be progressively more difficult.

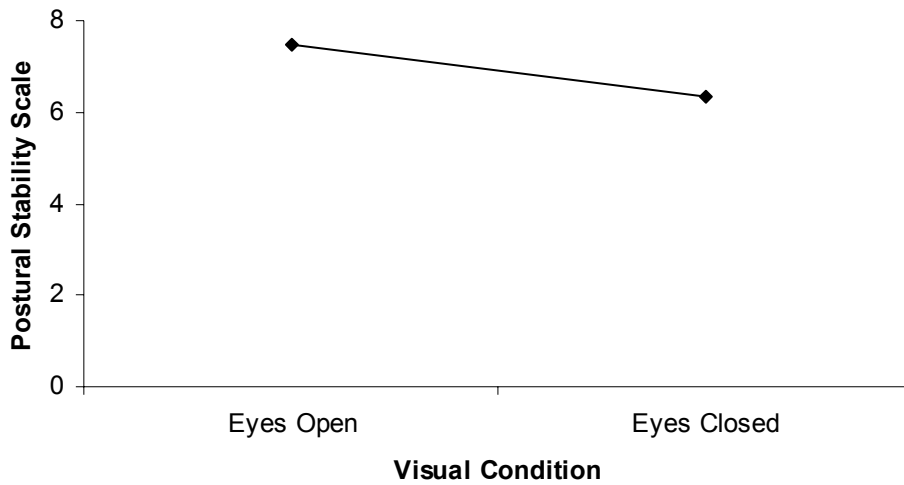


Figure 37. Postural stability ratings with (eyes open) and without (eyes closed) the presence of visual cues.

Postural stability ratings were not significantly affected by increased mental demands associated with the mental arithmetic (Figure 38). The trend in the data, although not significant ($p=0.60$), implied that postural stability ratings increased slightly with increases in mental demands.

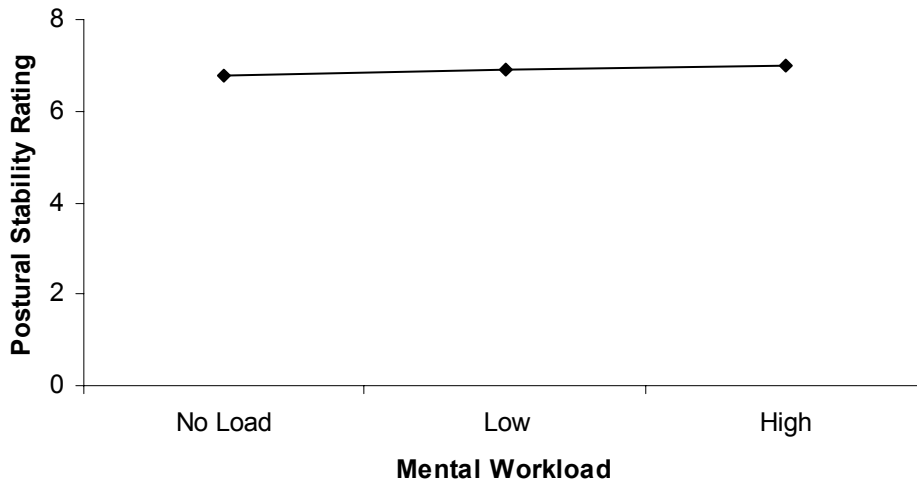


Figure 38. Postural stability ratings for varying mental workload levels.

5.3.3. Subjective assessment of mental workload

The perceived difficulty of the three mental activity levels was assessed using a VA scale. The difficulty of the three mental tasks was assessed as being significantly different, increasing with larger demands of mental resources (Figure 39). Subjective assessments of mental workload, using the VA Scale, were sensitive to changes in postural stance. VA ratings increased with increases in difficulty of the postural stance (Figure 40). The absence of visual cues also increased subjective mental workload assessments, reflected in higher ratings (Figure 41).

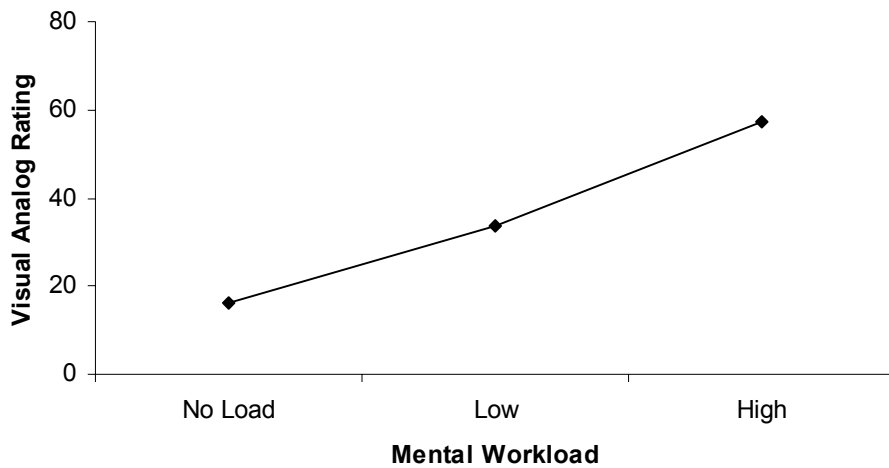


Figure 39. Mental workload assessment scores, using a Visual Analog scale, for conditions of varying mental workload.

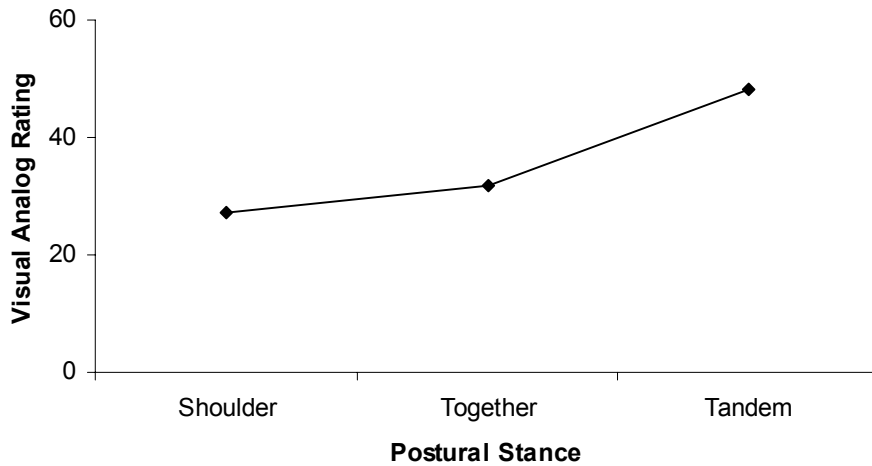


Figure 40. Mental workload assessment scores, using a Visual Analog scale, for conditions of varying postural stance that increase in difficulty.

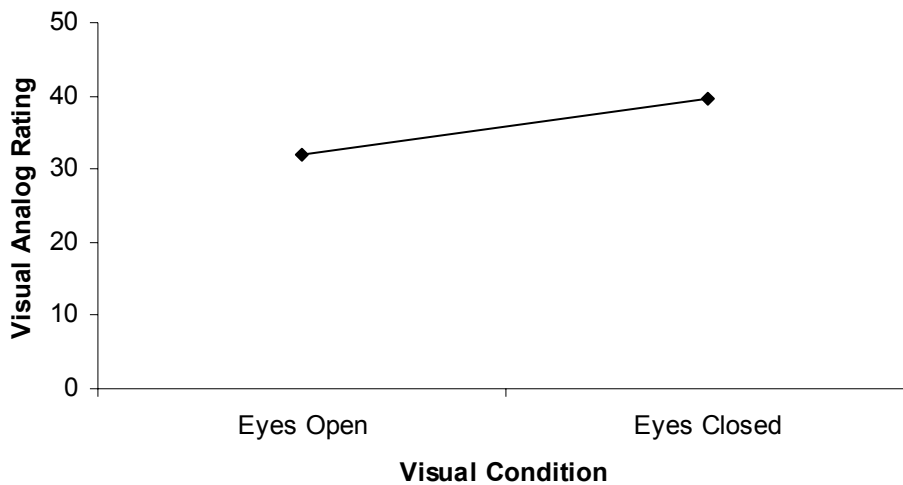


Figure 41. Changes in subjective ratings of mental workload, using a Visual Analog scale, associated with the absence of visual cues throughout the condition.

5.3.4. Effect of interactions

The effects of interactions between the three factors investigated were examined for all dependent measures. The three-way interaction and the interaction between mental workload and visual condition were not significant for any of the dependent measures. VA ratings were significantly affected by the interaction between mental workload and postural stance, whereas the interaction between postural stance and visual condition was significant for all other dependent measures.

Mental workload assessments were greatest during the tandem stance. Increases in mental demands had a greater influence on VA ratings during easier postural stances. The difference in perceived mental workload between the three postural stances was significantly less at high levels of mental workload (Figure 42).

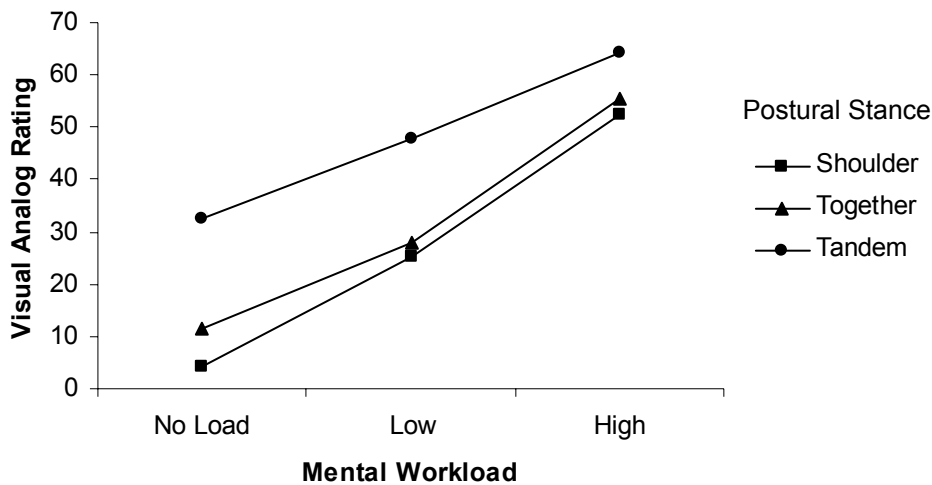


Figure 42. Perceptions of mental workload, using a Visual Analog scale, for varying postural stances and mental workload levels.

Changes in mean distance were dependent upon the visual condition. The mean distance decreased with eyes open as the postural stances became progressively more difficult. Conditions requiring the eyes to be closed, removing visual cues, were associated with increases in mean distance with increasing difficulty in postural stance (Figure 43). RMSD distance was also dependent upon the visual condition. The difference in RMSD during less demanding postural stances was significantly less than the other postural stances. RMSD was smallest with feet shoulder width apart but similar for the two more difficult postural stances, while visual cues were present. In contrast, RMSD continued to increase with the difficulty of the postural stances when eyes were closed and no visual cues were provided (Figure 44).

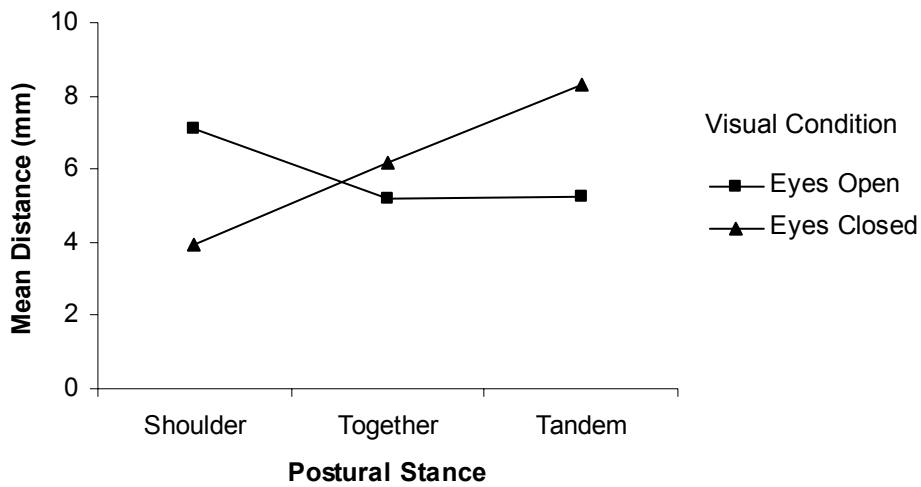


Figure 43. Mean distance for varying postural stances and visual conditions.

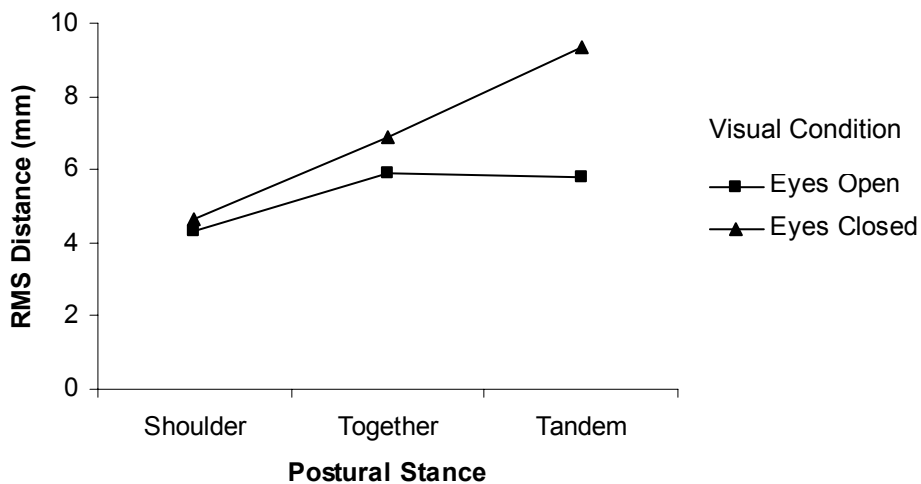


Figure 44. RMS distance for varying postural stances and visual conditions.

Mean and peak velocities were affected similarly by changes in postural stance and visual condition. Differences in velocities were minimal during the shoulder width conditions, but deviated significantly as the postural stance became more difficult. Conditions requiring the absence of visual cues were influenced more significantly with increases in postural stance difficulty, indicated by the increase in vertical separation between the curves (Figure 45 and Figure 46). Sway area, influenced by the velocity of

sway, behaved similarly to the velocities for different postural stances and visual conditions (Figure 47). Changes in sway area during the shoulder width condition are negligible, but differences increased with postural stance. Difficult postural stances (e.g. tandem) combined with the absence of visual cues resulted in the highest sway area.

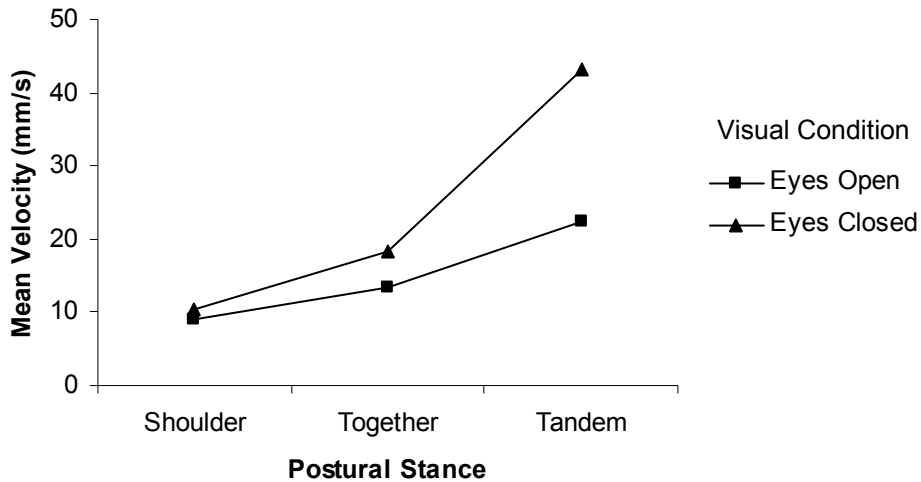


Figure 45. Mean velocity for varying postural stances and visual conditions.

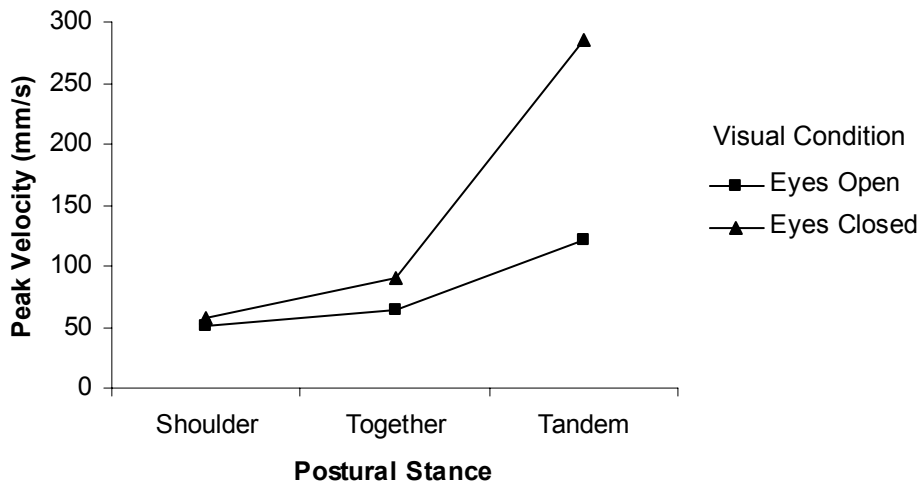


Figure 46. Peak velocity for varying postural stances and visual conditions.

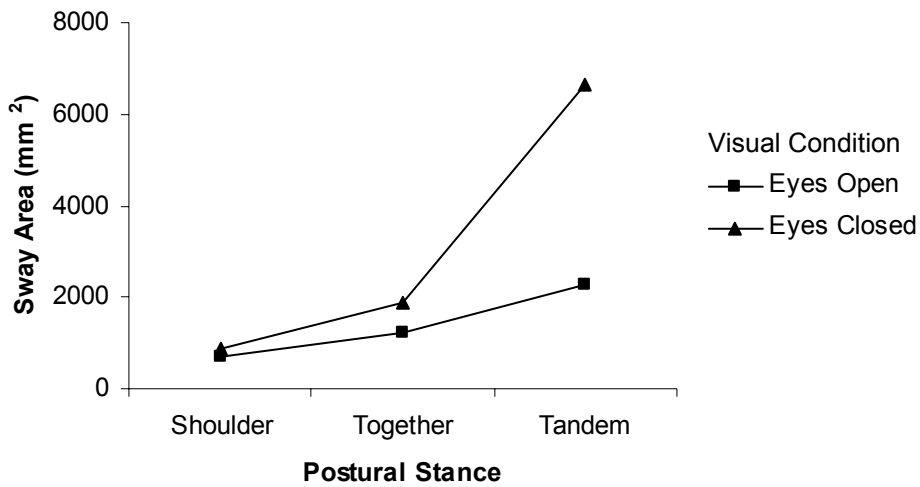


Figure 47. Sway area for varying postural stances and visual conditions.

During the shoulder width conditions, postural stability ratings were similar for eyes open and closed. The moderate increase in difficulty associated with the feet placed together raised stability ratings with eyes open, but significantly declined with eyes closed. Both sets of ratings decreased during the tandem stance, with the difference being similar to that for the feet together conditions (Figure 48).

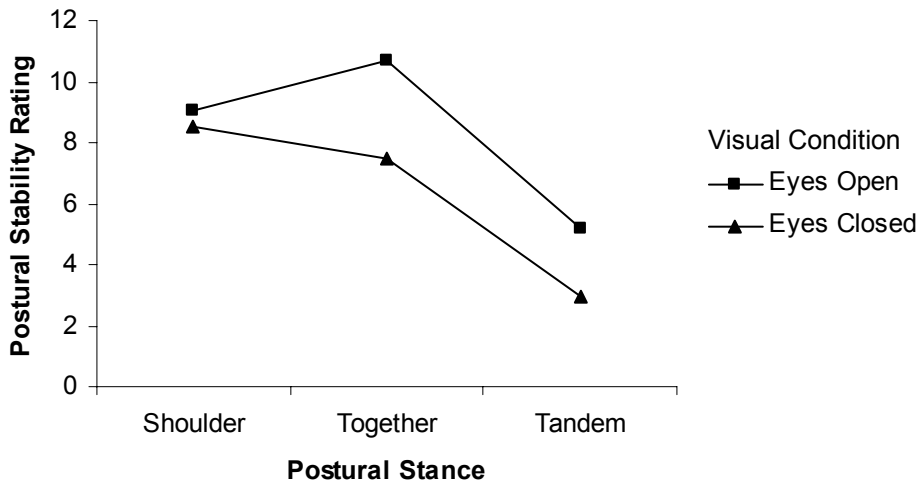


Figure 48. Postural stability ratings for varying postural stances and visual conditions.

The interaction between mental workload and postural stance did not significantly affect postural stability ratings ($p=0.33$). A trend existed that indicated an increase in perceived postural stability for the two easier postural stances (shoulder width and feet together), but a decrease in ratings during the tandem conditions (Figure 49).

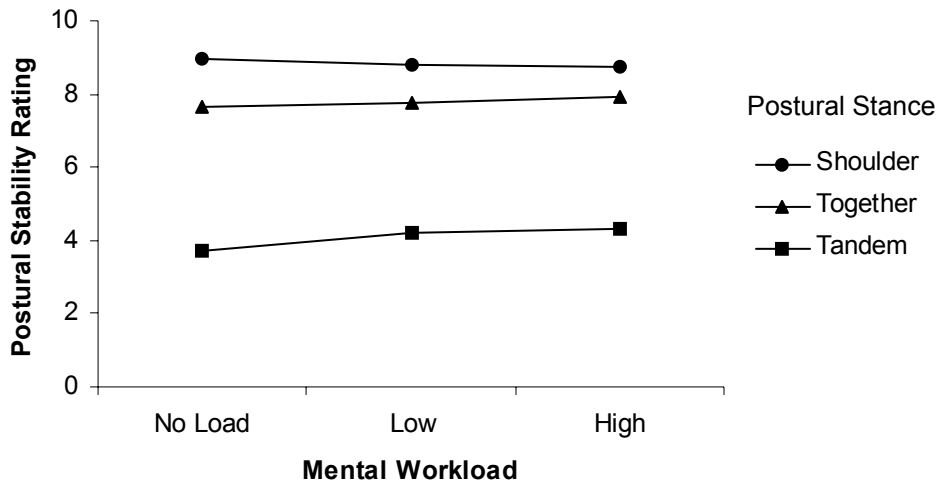


Figure 49. Postural stability ratings for varying mental workload and postural stances.

5.3.5. Correlations between subjective and objective measures

The line best fitting the postural stability ratings and the objective measures of postural sway was logarithmic. Figure 50 shows an example of the relationship between peak velocity and postural stability ratings. Ratings were averaged across all participants. Correlations (r) between subjective and objective measures of postural stability, after logarithmic transformation, were determined (Table 8). All correlations were significant.

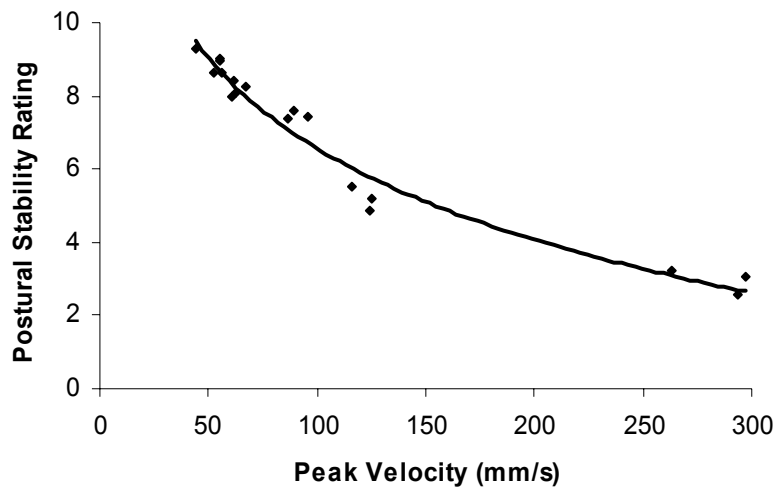


Figure 50. Relations between subjective ratings and peak velocity averaged across conditions. The data points are best fitted through a logarithmic model.

The objective measures of postural sway were significantly correlated with each other ($r = 0.71 - 0.99$) and the subjective postural stability ratings ($r = -0.43 - -0.71$). As expected, negative correlations indicated that increases in postural sway were reflected by lower ratings of perceived stability. Correlations between the velocity measures (peak and mean velocity) and postural stability ratings ($r = -0.66$ and $r = -0.71$) were higher than those between the distance measures (mean and RMS distance) and postural stability ratings ($r = -0.43$ and $r = -0.44$).

Table 8. Correlations between logarithmically transformed subjective (VA – Visual Analog ratings; PSR – postural stability ratings) and objective measures (MD – mean distance; MV – mean velocity; PV – peak velocity; RMSD – RMS distance; SA – sway area).

	PSR	MD	MV	PV	RMSD	SA
VA	-0.36	0.10	0.32	0.29	0.10	0.24
PSR		-0.44	-0.71	-0.66	-0.43	-0.60
MD			0.72	0.71	0.99	0.81
MV				0.93	0.71	0.87
PV					0.71	0.83
RMSD						0.80

5.4. Discussion

Maintaining balance during an upright stance can be almost automatic for a healthy individual in some situations. Changes in visual conditions and postural stances, however, may create situations that require attentional resources to be allocated to this action. Postural sway increased when visual cues were removed. These conditions required the individual to only rely on two systems to maintain balance since input from the visual system was removed. Changes in postural stance affected the inputs from the somatosensory system. Individuals responded to these inputs during difficult stances by increasing postural sway. These results concur with several studies that have investigated the effects of visual cues and postural stance on objective measures of postural sway (e.g. Duarte and Zatsiorsky, 2002; Goldie, Bach, and Evans, 1989; Hu, Hung, Huang, Peng, and Shen, 1996; Kuo, Speers, Peterka, and Horak, 1998). Individuals perceived the changes in postural sway and reflected the differences in the postural stability ratings. Schieppati et al. (1999) also found that postural stability ratings were sensitive to changes in visual condition, but did not find significant changes for postural stance. Postural stance was only evaluated, however, for feet shoulder width apart and together.

The effect of mental workload on postural sway is less obvious and depends on the complexity of both tasks (Brown et al., 1999; Dault et al., 2001a). In the present study, mental workload significantly affected the distance measures, but the velocity measures and sway area were not affected. The distance of the movement by the COP was reduced with the addition of a complex mental task. Hunter and Hoffman (2001) also found decreased postural sway for young adults when a memory task was introduced. Shumway-Cook et al. (1997) indicated that the affect of mental workload on postural sway is dependent on the age of the individual. Further research is required to clarify the extent that the result found in the present study generalizes to other populations.

Mental workload significantly affected some objective measures of postural sway, but had no substantial affect on perceptions of postural stability. This result indicated that perceptions of postural stability were more dependent on the velocity of sway and not the magnitude of the distance. The alternative is that the addition of a complex mental task reduces the accuracy of the individual's ability to perceive postural stability.

Three distinct levels of mental workload were established, as indicated by the significantly different VA scale ratings for each level. Increased task difficulty, by altering visual conditions or postural stance, significantly increased VA scale ratings. Alterations in the ratings from the VA Scale were not expected since the scale does not have any physical components. Changes in conditions may have caused detrimental effects on mental performance, which would correspond to the increased VA Scale ratings. Further research concerning the changes in cognitive performance during similar conditions is necessary to establish the sensitivity of the scale.

5.4.1. Effects of interactions

Subjective assessments of mental workload increased with increases in mental demands and postural demands. The interaction of mental workload and postural stance indicated that as the postural stance became more difficult, the variability in the perceptions of mental workload decreased. Ratings were very similar with feet shoulder width apart and together. The mental demands perceived during these two stances, without mental arithmetic, were minimal. In contrast, the tandem stance was associated with moderately high levels of mental workload without the mental arithmetic requirement. The introduction of an arithmetic task and increasing the difficulty of the problems more significantly affected perceptions of mental workload during the easier postural stances.

Interactions between the postural stances and visual conditions emphasized the role of the visual system in maintaining balance. With eyes open, mean distance decreased as the postural stance became more difficult to maintain. Although RMSD increased slightly between shoulder width conditions and feet together conditions, no substantial changes were reflected as the postural stance became more difficult. Both dependent measures relating to distance consistently increased when no visual cues were present. The strategies employed by individuals seemed to have differed for the two visual conditions. When visual cues are present, individuals were able to restrict movement when balance was compromised by a novel or difficult postural stance (Dault et al., 2001b). The absence of visual cues removed the input necessary for this adjustment in the eyes closed conditions. Although velocity and sway area increased

when visual cues were available, the effect of postural stance was less substantial than during the eyes closed conditions.

Postural sway and perceptions of postural stability were not substantially affected during the conditions requiring the feet to be shoulder width apart. Maintaining this natural position was relatively automatic, so allocation of minimal resources was necessary to maintain balance. Increased difficulty in postural stance required attentional resources to be allocated to maintaining balance, including a greater reliance on input from the visual and somatosensory systems. Less useful inputs from two of the systems responsible for maintaining balance combined to create an additive effect on postural sway and perceptions of postural stability.

Several participants indicated that the concurrent mental task, while maintaining a novel or difficult postural stance, reduced the attention allocated to maintaining balance. In these situations, the individuals reported feeling more stable than during conditions involving the same postural stance but requiring no mental arithmetic. Although the interaction between mental workload and postural stance was not significant, the trends in the data substantiate this finding. Postural stability ratings increased with increases in mental workload during the more difficult postural stances, but decreased for the shoulder width conditions. All participants did not express this attitude; therefore, future research would be necessary to determine the implication of this idea.

5.4.2. Correlations between subjective and objective measures

Relatively wide variations were found in the postural sway measures for different conditions. Correlations between the objective postural sway measures were very high. As expected, the correlations were highest between the two distance measures and the two measures of velocity.

A logarithmic model best described the relationship between the objective postural sway measures and ratings of postural stability. The postural stability ratings did not decrease proportionally to the increases in postural sway. Perceptions of postural stability reflected the velocity of postural sway more so than the distance measures, indicated by higher correlations.

Participants were able to assess postural stability, using similar neural mechanisms that permit individuals to psychophysically evaluate the intensity of stimuli (e.g. sound). Perceptual ratings of postural stability were inverted to determine the power function relating postural stability ratings to objective measures of postural sway. The exponents of the power functions are provided in Table 9 and were similar to those relating sensory magnitude to stimulus intensity (e.g. loudness – 0.67), as indicated by Gescheider (1985). Further research is needed to determine the impact of the variability within the stimulus intensity (objective postural sway measures) on the components of the power function. Power functions examined by Gescheider (1985) were all based on fixed stimulus intensity levels.

Table 9. Exponents for power functions relating perceived postural stability and objective postural sway measures.

Postural Sway Measure	Exponent
Mean Distance	0.65
RMS Distance	0.62
Mean Velocity	0.83
Peak Velocity	0.59
Sway Area	0.39

Maintenance of quiet stance is generally performed without conscious awareness by the individual of the adjustments required to maintain a correct posture. The present study and Schieppati et al. (1999) determined that individuals have the ability to access this process and reasonably accurately evaluate the magnitude of the adjustments.

5.4.3. Limitations

Control strategies for maintaining posture may be affected by age (Brown et al., 1999). Participants within this study were all young adults. Further investigation is needed to determine whether the results also occur within an older population. Observed changes in posturographic measures do not prove that balance control was compromised and do not necessarily imply a higher risk of falls. COP measures are generally recognized as providing indirect evidence only. Finally, the possibly confounding effect of articulation on objective measures of postural sway was not considered.

5.5. Conclusions

Limited resource sharing occurred at low levels of mental workload accompanied by visual cues and an effortless postural stance because the tasks required different processing modalities. Yardley et al. (2001) determined that was unlikely that dual task interference between balancing and mental activity is due to competition for spatial processing resources. Postural sway increased with task difficulty, regardless of the source (i.e. postural stance, visual condition, mental workload). Interference between mental activity and postural control can be attributed primarily to general capacity limitations, and is hence proportional to the attentional demands of both tasks, as described by Kahneman (1973).

Perceptions of postural stability were non-linearly related to objective measures of postural sway, caused by changes in postural stance and visual conditions. The addition of mental workload did not alter this relationship. Several factors increase postural sway and may be responsible for increased risk of falls. Variables found to substantially influence balance should be regulated to reduce occurrences of postural instability. Since decrements in balance are well perceived, subjective assessment tools may be incorporated in control strategies.

6. SUMMARY

Workload is established by the interaction between the demands of a task, the circumstances under which it is performed, and the skills, behaviors, and perceptions of the individual. Workload is defined as the cost incurred by an individual, given their capacities, while achieving a particular level of performance on a task with specific demands. The fields of physical and mental workload assessment have been widely, though separately, investigated. In contrast, measurement of general workload, for tasks that incorporate both physical and mental demands, has received less attention. There have been attempts to identify a physiological measure of concurrent physical and mental workload, as yet there has been no work towards developing a subjective assessment tool.

The present research examined concurrent tasks, investigated the ability of individuals to perform the tasks, and determined whether workload could be effectively assessed using existing subjective measures. Interactive effects of physical and mental workload on subjective workload assessment were investigated. Measurements of task performance were evaluated to establish which subjective assessments were most precise and easily acquired. Results from the present studies indicated that in conjunction with degradation of performance, physical activity influenced objective and subjective mental workload assessment. Individuals seemed to be more sensitive to physiological reactions due to physical demands rather than mental demands.

The theory proposed within the Kahneman Capacity Model was supported by the present findings. Increases in difficulty of the task, physical or mental, caused performance to degrade. Allocation of resources differed for each combination of difficulty levels, causing alterations in performance, although the types of resources required did not change. Based on multiple resource theory, time-sharing efficiency is related to the types of resources required to perform each task. Increases in difficulty, not accompanied by changes in required resources, should not affect performance. The EPIC model states that an unlimited number of production rules can be assessed simultaneously, but does not clarify the level of interference between tasks.

The utility of existing subjective assessment tools created for one domain appeared to be limited when evaluating multi-task situations requiring substantial mental and physical activity. Assessment of overall workload during multi-task situations requires the development of a new tool that adjusts for this incongruity. A unidimensional tool is suggested as a screening tool to identify situations requiring excessive or increased mental workload. Alternative methods, possibly a new multidimensional tool or combination of existing tools, should be developed to obtain more detailed information regarding overall workload based on physical and mental demands so ratings of workload for different tasks may be compared.

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**APPENDIX A – A SUBSET OF ARITHMETIC TASKS USED TO GENERATE
MENTAL WORKLOAD**

Addition

16	15	31
17	9	26
19	19	38
5	17	22
20	3	23
5	15	20
6	7	13
4	6	10
6	12	18
4	3	7
4	18	22
19	15	34
1	7	8
1	13	14
18	20	38
3	9	12
10	6	16
1	10	11
20	12	32
14	4	18
12	12	24
15	13	28
16	20	36
1	7	8
15	2	17

Subtraction

74	62	12
62	40	22
94	72	22
79	69	10
60	35	25
60	74	-14
92	98	-6
47	46	1
79	96	-17
30	62	-32
28	55	-27
83	48	35
82	40	42
93	99	-6
23	67	-44
23	59	-36
80	96	-16
24	47	-23
50	72	-22
73	91	-18
31	91	-60
55	50	5
40	75	-35
95	80	15
46	53	-7

Multiplication

9	43	387
5	24	120
6	22	132
4	24	96
5	41	205
5	40	200
5	38	190
9	11	99
8	20	160
4	15	60
5	18	90
7	39	273
8	35	280
8	46	368
5	35	175
8	25	200
8	36	288
4	25	100
8	19	152
4	42	168
4	19	76
7	25	175
4	35	140
6	38	228
8	19	152

APPENDIX B – SCREENING DIGITS WITH ANSWERS

Addition:

4	20	24
6	8	14
12	15	27
6	7	13
14	11	25
17	9	26
3	13	16
8	4	12
12	5	17
10	1	11

Multiplication:

9	50	450
4	30	120
6	34	204
7	19	133
8	39	312
4	26	104
9	25	225
5	13	65
7	48	336
5	15	75

Subtraction:

87	38	49
79	92	-13
98	50	48
93	38	55
65	37	28
26	83	-57
76	30	46
62	97	-35
54	58	-4
84	39	45

**APPENDIX C – EXAMPLES OF SUBTRACTION TASKS USED TO MAINTAIN
CONSTANT MENTAL WORKLOAD**

24	92	-68
42	73	-31
52	47	5
25	79	-54
52	71	-19
82	47	35
64	69	-5
73	60	13
74	74	0
41	76	-35
50	28	22
64	88	-24
37	77	-40
52	26	26
53	71	-18
84	60	24
51	92	-41
99	61	38
41	81	-40
42	82	-40
66	88	-22
21	45	-24
91	64	27
98	89	9
42	29	13
83	31	52
29	37	-8

APPENDIX D – SCREENING DIGITS FOR SUBTRACTION WITH ANSWERS

89	36	53
79	95	-16
96	49	47
93	38	55
65	37	28
28	83	-55
76	30	46
62	95	-33
54	60	-6
82	39	43

VITA

ANGELA TERESE DIDOMENICO was born on July 20, 1970, in New Haven, Connecticut. She received her Bachelor of Arts in Mathematics from the University of Connecticut in May 1992. In 1993, after spending fifteen months working at the University of Connecticut's School of Business and Real Estate Center, Angela decided to return to school to pursue a graduate degree in Mathematics. Studying mathematics provided her the opportunity to teach other students, both in the classroom and individually. She received her Master of Science in Mathematics from Virginia Polytechnic Institute and State University in May 1996. While concluding her mathematics requirements, she discovered Human Factors Engineering and joined the Industrial and Systems Engineering Department. The National Institute for Occupational Safety and Health funded her master's research in the Industrial Ergonomics Laboratory, where she received her Master of Science in Industrial and Systems Engineering. The Army Research Laboratories of Aberdeen, Maryland provided funding for her doctoral research. She is currently an active member of the Human Factors and Ergonomics Society, American Society of Biomechanics, American Society of Safety Engineers, and Alpha Pi Mu.