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A theoretical framework for evaluating mental workload resources in human systems design for manufacturing operations

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ABSTRACT

As the nature of manufacturing work is changing, requiring more cognitive demands, there is a need to develop system models for measuring and predicting human performance in repetitive task operations. This paper presents a theoretical framework, which provides a systematic approach for measuring mental workload using a combination of analytical and empirical techniques: human performance modeling with a computer simulation and mathematical modeling, along with physiological, subjective and performance measures. For this study, the Air Force MATB, which is a re-development of the NASA simulation tool, was used to model multitasking in a controlled environment to validate the theoretical framework. The independent variable of task complexity was measured, in the modeling of resource demands for a cleaning-inspection process and a final inspection process, using three dependent variables (subjective, physiological and performance measures) with a total of four responses (NASA-TLX, Workload Profile, fixation duration and human error probability). The results indicate no significant difference among the response variables for each task complexity level, indicating the model accurately represents the operator's workload. Additional analysis shows accurate predication from the model in analyzing workload peaks.

Relevance to industry: This theoretical framework is designed to evaluate operator mental workload utilization in the manufacturing domain. This is important because manufacturing work is changing by requiring more multitasking roles, which increases cognitive demand. Therefore, the industry needs models that can predict operator performance and mental workload for improved productivity.

1. Introduction

Manufacturing is a human-driven transformation process that applies energy and manpower to produce consumer products of economic value (Spath et al., 2012). In repetitive task operations like manufacturing systems, performance optimization influences safety in the environment and profitability. In the general fast pace of manufacturing operations, there is the potential for operator errors, which correlates to possible safety issues and loss of revenue. For example, an assembly worker performing a manual assembly task is constantly exposed to situations with varying mental demands. Aspects of these demands to consider are the amount of information, time pressure, interruptions, rapid decisions, component batch sizes and the work station physical layout (Lindblom and Thorvald, 2014). A high workload task that can encompass each of these aspects is that of inspection. The traditional role of quality inspectors is changing from dedicated quality inspectors to operators who perform multiple duties while attempting to perform inspection tasks (Pesante et al., 2001). This transforms the task from a sequential task to one of multitasking. Multitasking is becoming more prevalent in manufacturing operations.

There is a large body of literature on physical ergonomics for process improvements, but limited studies on cognitive ergonomics relative to mental workload (MWL) in manufacturing. Cognitive ergonomics focuses on the quality of work, including the outcome, versus traditional or physical ergonomics looking at the quality of working (Hollnagel, 1997). Traditional ergonomics focused on reducing operator fatigue and discomforts in efforts to increase throughput. However, the nature of human work has changed dramatically from working with the body to working more with the mind as industrial systems have become more automated. Also, the increased responsibility of technology along with the use of complex procedures have imposed more demand on operators (Stanton et al., 2010). Instead of physical endurance and strength,

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sustained attention and problem solving skills have become more important. Also, physically demanding work that is performed simultaneously with a cognitive task can influence mental workload by weakening mental processing or decreasing performance (DiDomenico and Nussbaum, 2011). Therefore, in order to improve human systems design for performance in manufacturing, the system design should include cognitive ergonomics in order to evaluate the cognitive elements of a task. As a result, the aim of this research is to explore the theory of cognitive ergonomics in manufacturing operations that require repetitive tasks. A theoretical framework, using a combination of analytical and empirical techniques, is proposed to improve operator performance and human-system design through the use of mental workload applications to adjust operator mental workload utilization. The structure of this paper is as follows: Section 2 discusses theory relative to creating the theoretical framework. Section 3 reviews the experimental framework and methodology. Section 4 presents the research findings. Lastly, Section 5 presents the conclusion and discussion.

2. Theory

The following concepts of Cognitive Ergonomics, Mental Workload (MWL) and the Multiple Resource Theory (MRT) offer useful information for exploring mental workload applications in manufacturing operations. Each of these topics are inputs into the theoretical framework presented here.

2.1. Cognitive ergonomics

Cognitive ergonomics studies processes during work with a concentration in understanding a situation to support reliable, effective and satisfactory performance (Canas et al., 2011). It evaluates problems relative to attention distribution, decision making, formation of learning skills, usability of human-computer systems, cognitive aspects of mental load, stress and human errors at work (Canas et al., 2011). Numerically controlled machines, group technology, cellular manufacturing and Just-In-Time production systems have revolutionized the manner in which products are designed and manufactured; these advances have transformed the role of the human operator in the manufacturing environment (Pesante et al., 2001). Cognitive ergonomics deals with the interaction between tools and the user, emphasizing the cognitive processes of understanding, reasoning, and the use of knowledge (Green and Hoc, 1991). It is the ergonomics of mental processes to improve operator performance by understanding how work affects the mind and how the mind affects work (Hollnagel, 1997). This concept focuses on finding a balance between the human's cognitive abilities and limitations, as well as the machine, task and environment (Kramer, 2009). This can lead to a reduction in errors and better performance in the manufacturing domain. The application of cognitive ergonomics in manufacturing operations is important because the nature of human work in manufacturing has changed considerably from working with the body to working more with the mind with the implementation of more automation and complex process procedures.

2.2. Mental workload

With repetitive task operations, there is interaction between the operator and an assigned task; this is referred to as mental workload (MWL) or simply ‘workload’. This is an important measurement because it provides awareness as to where unacceptable performance may result from an increase in task demands. The demands on a task or grouping of tasks may include completing physical actions and/or executing cognitive tasks (DiDomenico and Nussbaum, 2008). Mental workload describes the demands of tasks, that require the limited information processing capability of the brain, in much of the same way that physical workload characterizes the energy demand upon the muscles (Wickens et al., 2013). The assessment of mental workload is an important aspect in the design and evaluation of occupational tasks (DiDomenico and Nussbaum, 2011). The interaction between an operator and an assigned task is an important measurement because it provides awareness as to where increased task demands could lead to a negative impact on human performance. Also, workload rises when the number or difficulty of tasks required to complete a goal increases, or when the times allocated for task completion decreases (Colombi et al., 2012). Regulating task demands, such that the operator is neither under-loaded nor overloaded, can increase safety, health, comfort and long-range productivity (Rubio et al., 2004), because high cognitive load for pro-longed periods can lead to inefficient processes, poor performance as well as ergonomic and mental health symptoms (Lindblom and Thorvald, 2014). Therefore, mental workload has a direct effect on an operator's ability to sustain or reach desired performance levels (Xie and Salvendy, 2000). As cited by Jung and Jung (2001), the concept of MWL is associated with the difference between the amount of resources available to a person and the amount of resources needed for the task. At the point when task demands exceed operator capacity, high levels of MWL occur (Loft et al., 2007). The workload can be modified by adjusting available resources within the person, or the required task demands on the operator. The next section discusses the application of the Multiple Resource Theory to predict mental resources and demand usage while performing tasks.

2.3. Multiple Resource Theory (MRT)

Multiple Resource Theory provides a predictive model to better understand the relationship between resources and demands while multi-tasking in a complex environment (Wickens, 2002). When an individual performs a task, they expend mental operations, and to some extent, each operation deploys mental processing resources crucial to completing the task (Mitchell, 2003). People are capable of multi-tasking until task demands exceed available resources. In order to provide safe and efficient operations of complex systems, the mental workload required by the users should not exceed their capacity (Hertzum and Holmegaard, 2013). According to MRT, the human mind can allocate several resources to task demands either individually or collectively to include: visual, auditory, cognitive, motor, and speech. When task demands overlap, fewer resources are available and MRT predicts that performance will degrade when multiple tasks require competing resources. This could lead to a compromise in system safety and effectiveness.

MRT can predict performance breakdowns in high workload circumstances, such as tasks that require an operator to perform two or more activities at one time. This model can make practical predictions relative to performance breakdown regarding a human operator's ability to accomplish tasks (Wickens, 2002). A significant application of MRT, and one employed in this study, is its ability to recommend design or task changes when conditions of multitasking create resource overload (Wickens, 2008). Examples of reducing resource overload may include automating parts of tasks, reassigning parts of a task to another operator, or changing task procedures such that process steps are performed sequentially instead of concurrently (Wickens et al., 2013). MRT uses four dimensions in the multiple resource model that justifies the variance in time-sharing of performance, and each dimension has two discrete levels (Wickens, 2002). These dimensions are processing stages, perceptual modalities, visual channels and processing

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