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What is the relationship between mental workload factors and cognitive load types?

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ABSTRACT

The present study tested the hypothesis of an additive interaction between intrinsic, extraneous and germane cognitive load, by manipulating factors of mental workload assumed to have a specific effect on either type of cognitive load. The study of cognitive load factors and their interaction is essential if we are to improve workers' wellbeing and safety at work. High cognitive load requires the individual to allocate extra resources to entering information. It is thought that this demand for extra resources may reduce processing efficiency and performance. The present study tested the effects of three factors thought to act on either cognitive load type, i.e. task difficulty, time pressure and alertness in a working memory task. Results revealed additive effects of task difficulty and time pressure, and a modulation by alertness on behavioral, subjective and psychophysiological workload measures. Mental overload can be the result of a combination of task-related components, but its occurrence may also depend on subject-related characteristics, including alertness. Solutions designed to reduce incidents and accidents at work should consider work organization in addition to task constraints in so far that both these factors may interfere with mental workload.

1. Introduction

Everyday work processes are hindered by disruptions, time pressure, and stress, all of which contribute to health and safety problems, and are extremely wasteful of human resources in the workplace. A comprehensive survey (Kompier et al., 2000) showed that 25% of European workers perceived stress as the major cause of health problems and lower work performance, even though they simultaneously reported that their working conditions had improved, and that occupational health services had been expanded. According to Docherty et al. (2002), since the beginning of the 1990s, work intensity has grown because management is increasingly driven by short-term competitiveness goals. The intervals between technological and organizational changes are shorter, as are cycles of change in the workplace (Seppälä, 2009). Increases in work intensity generate mental overload and reduce work performance. Consequently, the study of mental workload factors and the way they interact is essential if we are to improve workers' wellbeing and safety at work.

The present study focuses on mental workload that can be defined as the cognitive demand of a task (Miyake, 2001). In the work place, mental workload may be evaluated by recording psychophysiological components, task performance, and self-rating questionnaires or scales. A brief review of the literature will highlight the sensitivity of mental workload measures.

1.1. Mental workload measures

The tools used to measure a particular type of cognitive load can be divided into three main categories: subjective measures, performance measures, and psychophysiological measures.

1.1.1. Subjective measures

There are two most commonly used techniques of subjective mental workload. First, the NASA-Task Load Index (NASA-TLX; Hart and Staveland, 1988) which includes six subscales exploring the Mental Demand, Physical Demand, Temporal Demand, Own Performance, Effort, and Frustration Level. Second, the subjective workload assessment technique (SWAT; Reid and Nygren, 1988) describes three dimensions of operator workload: Time Load, Mental Effort Load and Psychological Stress Load. The two subjective mental workload techniques have been suggested to be relatively similar (Miyake, 2001), and more especially the Time Load and Temporal Demand dimensions, the Mental Effort Load and Mental Demand and Effort dimensions, and the Psychological Stress Load and Frustration dimensions. Both techniques are largely used in the field of aeronautics, as shown for instance in a study by Collet et al. (2009) that revealed a positive correlation between the number of aircrafts to control and the NASA-TLX score in air traffic controllers. Further, controllers' self-rated workload closely paralleled the change in the number of aircrafts to be controlled, indicating a high sensitivity of NASA-TLX to small workload changes.

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1.1.2. Performance measures

Within this group of methods, the participants' mental workload is inferred from their overt behavior or performance, in particular response accuracy and response latency. Chi and Lin (1997) demonstrated a trade-off between these performances criteria, as the time needed to complete a task increased when accuracy requirements increased, whereas a decrease in accuracy occurred when task rapidity requirements increased. As performance measures may not reflect subtle changes in mental workload, and they are appropriate only if a task yields a sufficient rate of overt behavior, Paas and van Merriënboer (1993) proposed to combine performance measures and subjective measures to determine a subject's relative task efficiency. Mental efficiency (E) may be determined by the formula $E=(P-R)/2$, where P corresponds to performance and R to mental effort. Mental effort would refer to the cognitive capacity that is actually allocated to the task, and the subject's performance would reflect mental load, mental effort, and the causal factors described above. Mental load in turn would indicate the portion of cognitive load that is imposed exclusively by the task and by environmental demands (Kablan and Erden, 2007; Kirschner, 2002). According to these authors, mental load, mental effort, and performance constitute the three measurable dimensions of cognitive load. They argued that the subjects' behavior is more efficient if their performance is better than might be expected on the basis of the mental effort they invest and/or if the mental effort they invest is lower than might be expected on the basis of their performance. Accordingly, high performance and low mental effort would be the most efficient combination and, conversely, low performance and high mental effort the least efficient combination. An alternative method to overcome these methodological difficulties is to construct a performance index taking into account both response accuracy and response latency. Thus, Fournier et al. (1999) evaluated subjects' behavioral responses in a multi-task design by calculating a composite standardized Z-score for each subject. For each task, the ratio of RT by the proportion of correct responses was weighted by one-quarter and these corrected ratios were summed up. Results revealed that global performance decreased as workload increased and that performance improved with training, especially in the high workload conditions.

1.1.3. Psychophysiological measures

Changes in various bodily processes and states have also been reported with changes in mental workload. One major advantage of psychophysiological measures is the continuous availability of bodily data, allowing load to be measured at a high rate and with a high degree of sensitivity, even in situations in which overt behavior is relatively rare (Paas, 1992). However, psychophysiological measures are also very sensitive to physical effort and will reflect specific mental load variations only for activities involving little or no physical effort (Brünken et al., 2003). Several measures can be used to estimate mental workload: cardiac activity, electrooculogram, respiration or event-related potentials. Some studies have shown sensitivity of brain event-related changes to differing levels of workload. Particularly, cognitive processing would result in attenuation of the alpha brain electrical rhythm (Fournier et al., 1999; Gundel and Wilson, 1992). Advantage of these electrophysiological measures resulted in the temporal resolution in line with the dynamics of cognitive activity. However, the measurement of cardiac activity is the most popular physiological technique employed in the assessment of mental workload. More especially, heart rate variability (HRV) (Backs, 1995), was demonstrated to show systematic and reliable relationships with task demands (Mulder and Mulder, 1981; Tattersall and Hockey, 1995). Thus, HRV was reported in response to changes in operator workload and strategies, expressed by a high positive correlation for instance with the number of aircrafts in an air traffic control task.

Overall, mental workload studies revealed that the sensitivity of workload measures differs according to a number of factors, and in particular according to the cognitive task to be performed. This led to the proposal that several different mental workload categories should be distinguished, as has been suggested by Sweller in the educational field, in the late 1980s (Sweller, 1988). Sweller's cognitive load theory suggested that high mental workload would require the individual to allocate extra resources to entering information, and that the demand for extra resources may reduce processing efficiency and performance. The author distinguished three categories of cognitive load. “Intrinsic cognitive load” would refer to the load induced by the intrinsic nature of the items being processed, such as task difficulty, and would thus be fixed and innate to the task. “Extraneous cognitive load” induced by external factors, including situation, work organization, time pressure, and noise, would vary according to the demands of the instructional procedures (Sweller, 1994). Likewise, Paas and van Merriënboer (1994b) defined cognitive load as “… a multi-dimensional construct that represents the load that performing a particular task imposes on the cognitive system of a particular learner” (p. 122). Accordingly, cognitive load would be the result of an interaction between task demands and individual characteristics. The third cognitive load category, “germane cognitive load”, was defined as the load placed on working memory during schema formation and automation (Paas et al., 2003a; Sweller et al., 1998). More recently, Schnotz and Kürschner (2007) proposed that germane load would correspond to the “conscious application of learning strategies (i.e. strategies, which are not automated yet), conscious search for patterns in the learning material in order to deliberately abstract cognitive schemata (i.e. mindful abstraction) and create semantic macrostructures, restructuring of problem representations in order to solve a task more easily (i.e. by insight), meta-cognitive processes that monitor cognition and learning” (p. 496).

According to cognitive load theory, intrinsic, extraneous, and germane cognitive loads are additive, in that the total load must not exceed available working memory resources if the task is to be completed. Further, relations between the three forms of cognitive load would be asymmetrical, since intrinsic cognitive load would represent the base load that may be reduced in particular by decreasing task difficulty. In consequence, only the working memory capacity remaining once resources have been allocated to deal with intrinsic cognitive load can be allocated to deal with extraneous and germane load. However, a large amount of free working memory capacity due to a low intrinsic load would not necessarily enhance task performance, as only a proportion of this free capacity can be allocated to germane load. In other words, whereas it is possible to solve very difficult tasks (high intrinsic load) without deep metacognitive reflection (low germane load), it is not possible to reflect deeply (high germane load) about a very easy task (low intrinsic load; Schnotz and Kürschner, 2007). In short, intrinsic and extraneous cognitive loads were proposed to be performance-based, while germane cognitive load would be learning-based.

In the present study, we propose to address cognitive load theory in the field of ergonomics Recently, Wiebe et al. (2010) made a similar attempt by testing the sensitivity of subjective mental workload techniques, typically used in the field of ergonomics: NASA-TLX and the subjective cognitive load measure (SCL) developed by Paas, Van Merriënboer, and others (Paas, 1992; Paas and van Merriënboer, 1994a, 1994b; Paas et al., 2003a, 2003b). By using Windell and Wiebe's (2007) approach to manipulate intrinsic and extraneous cognitive load, the authors showed that the NASA-TLX index was sensitive to changes in intrinsic cognitive load, although the SCL showed the greater degree of sensitivity. Indeed, in low extraneous load conditions TLX and SCL exhibited a comparable degree of sensitivity to intrinsic load, whereas in high extraneous load condition SCL was more sensitive. The relationship between intrinsic load and extraneous load was shown to be reciprocal as changes in extraneous load were more efficiently revealed by TLX when intrinsic load was low, but with higher accuracy with the SCL when intrinsic load was high. The authors accounted for these results by suggesting that the greater sensitivity of the SCL measure to changes in intrinsic load would