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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 contribute to its close relationship to learning performance at low levels of intrinsic load.

The present study tested the hypothesis of an additive interaction of mental workload types as has been proposed by Sweller and coworkers for different kinds of cognitive load. This interaction was tested by manipulating factors assumed to have a specific effect on one particular type of cognitive load, in line with the data in the literature.

1.2. Cognitive load factors

A brief review of the literature will focus on the cognitive load factors that have been manipulated in the present study.

1.2.1. Intrinsic cognitive load: task difficulty

Backs and Seljos (1994) demonstrated that task difficulty, determined by the number of items to be remembered, interfered with performance in a memory task. The mean error rate increased from 1.09% to 5% when subjects had to recall three items instead of one. More generally, the level of intrinsic cognitive load depends mainly on the number of elements to be assimilated simultaneously and, more especially, on the degree of element interactivity (the way in which the individual components of a task interact with each other; Ayres, 2006; Kalyuga et al., 2003; Sweller and Chandler, 1994).

By keeping other sources of (extraneous) cognitive load constant, Ayres (2006) showed that subjective measures were highly correlated with error rates in a problem-solving task, indicating that subjects directly assessed changes in intrinsic cognitive load. Likewise, task difficulty affects psychophysiological measures, particularly the components under the control of the autonomous nervous system. High cognitive load conditions were shown to give rise to elevated cardiac activity, respiratory activity, and blood glucose levels in order to provide the energy needed to perform the tasks (Carrol et al., 1986; Miyake, 2001).

1.2.2. Time pressure

Monod and Kapitaniak (1999) proposed that task difficulty would directly affect cognitive load, whereas time pressure would activate an emotional component and would thus have an indirect effect on cognitive load. Time pressure involves a conflict between the imposed completion time for a task and the time it actually takes to perform the task, and leads to highly emotional reactions. More especially, the individual's experience would raise anxiety, causing more attention resources to be allocated to the task and thereby increasing cognitive load. Thus, with increasing time pressure recall performance has been reported to decrease in controlled laboratory conditions (Backs and Seljos, 1994), and response accuracy in a shipbuilding simulation task (Inzana et al., 1996). More specifically, time pressure has proved to be one of the most common stressors in the work environment, where time may be part of a mediating process that influences perception of control (Koslowsky et al., 1995). Thus, increased heart rate is commonly reported in situations involving high tension and/or mental effort in real or simulated work conditions (Boucsein and Ottmann, 1996; Ritvanen et al., 2006), and has been shown to vary as a function of self-reported stress (Sloan et al., 1994; Ritvanen et al., 2006).

1.3. Arousal

A great deal of chronopsychological research has suggested that a subject's performance in a given task directly depends on his or her functional state (arousal; Monk and Leng, 1982). More specifically, in controlled laboratory conditions, higher immediate recall performance in short-term memory tasks was reported in the morning when low arousal would favor automatic processes like maintenance rehearsal, while delayed recall from long-term memory was enhanced in the evening, when high arousal would favor more complex semantic processing (Folkard, 1979; Folkard et al., 1976; Folkard and Monk, 1980; Monk and Embrey, 1981). This hypothesis has been further supported by field studies reporting higher performance in the evening than on early morning hours in more demanding discrimination or mnemonic task conditions in security agents or air traffic controllers (Mélan et al., 2007; Galy et al., 2008). Furthermore, task performance was positively correlated with operators' alertness, which in turn closely paralleled variations in subjects' functional state (Cariou et al., 2008). Thus chronopsychological studies have suggested that variations in arousal across the 24-hr day affect the amount of cognitive resources needed to maintain and process items in a memory store, probably due to the availability of automatic versus elaborate processing strategies. In line with this hypothesis, Smit et al. (2005) demonstrated that a decrease in arousal (increased EEG theta power) and alertness was associated with a performance decrement, elevated heart rate and higher self-reported mental workload.

To test for the additive effects of cognitive load factors, and their relationships with the subject's functional state, we explored the effects of task difficulty and time pressure, separately and simultaneously, at two different times of the day. The task used was a working memory task requiring subjects to recall the item presented on the previous trial (n-1). Manipulation of task difficulty (2- or 3-digit numbers) and time pressure (short or long response delays) determined four experimental task conditions so that task difficulty and time pressure were both low (condition 1), either task difficulty or time pressure was high (conditions 2 and 3), or both difficulty and time pressure were high (condition 4). In agreement with cognitive load theory, we expected to find a significant effect of task difficulty and time pressure (Ayres, 2006; Backs and Seljos, 1994; Kalyuga et al., 2003; Sweller and Chandler, 1994) on mental workload measures and, above all, an interaction between these two factors.

Subjects performed the task at two different times of the day, associated with low and high alertness respectively, at least in day-oriented individuals (Fabbri et al., 2007). As several studies have reported that time-of-day effects on task performance and physiological activation depend on task difficulty (Mélan et al., 2007; Galy et al., 2008), an interaction between subjects' alertness and task difficulty was expected. Likewise, subjects' alertness was expected to interact with time pressure, given that both factors have been shown to affect subjects' processing resources (Ayres, 2006; Backs and Seljos, 1994; Fabbri et al., 2007; Kalyuga et al., 2003; Sweller and Chandler, 1994). If the results confirmed these expectations, a three-way interaction should be observed between arousal, task difficulty and time pressure.

The effects on mental workload were explored by recording subjects' task performance, self-ratings of mental effort and perceived tension, and subjects' heart rate variations. The effect size of the different load measures would enable a comparison of their relative sensitivity to the load factors under investigation. Subjective measures were expected to be most sensitive, followed the performance measures and psychophysiological measures (Paas et al., 2003a, 2003b). Further, the mental efficiency index (Paas and van Merriënboer, 1993) was calculated in order to find out whether mental efficiency increased with low task difficulty, low time pressure and high arousal while performing a working memory task.

2. Method

2.1. Subjects

Thirty students (15 men and 15 women; $M_{age} = 22.7$; $SD = 1.612$; range = 20–26), studying for a Master of Arts or Master of Science degree, volunteered to take part in the study. Each participant stated that he or she had no brain or heart disorders and had normal vision. All subjects gave their full informed consent before taking part in the experiment. They attended two individual test sessions at the laboratory and were asked not to drink tea or coffee for 3 h prior to the start of the tests.

2.2. Material

2.2.1. Memory task

The effects of task difficulty and time pressure on recall performance were explored separately and simultaneously in four different task conditions (low difficulty and low time pressure; low difficulty and high time pressure; high difficulty and time low pressure; high difficulty and high time pressure). The order of the task conditions was randomized across subjects and consecutive task conditions were separated by a 4-min rest period (Fig. 1). There were 32 trials in each task condition and the subject had to recall the item presented in the previous trial (n-1). Items (black; system font; bold type; size 40) were displayed in random order, one by one, in the center of a white computer screen, for 1500 ms. A red asterisk then appeared in the middle of the screen, prompting the participant to enter number n-1 on a numeric keypad. ProLab was used to program random item presentation and to record the subjects' response latency and response accuracy.

Task difficulty was varied by asking the subject to recall either 2-digit numbers (low difficulty) or 3-digit (high difficulty) numbers. Time pressure was varied by manipulating the duration of the time limit, i.e., the amount of time before the next item was displayed. This interval lasted either 500 ms (high time pressure), or 3500 ms (low time pressure).

2.2.2. Differential heart rate

Changes in heart rate were recorded continuously throughout the experiment by an ambulatory heart rate (HR) monitor (Polar S610i™), comprising a transmitter worn around the chest and a receiver worn on the non-dominant wrist. The receiver stored the HR values before transferring them over an infrared connection to a computer where they were subsequently analyzed using Polar Precision Performance Software. During measurements, subjects were comfortably seated in an armchair, and were asked to relax for 20 min to make sure that baseline values were reached before starting the experiment. In each task condition, differential heart rate values corresponded to the difference between the subject's mean heart rate values recorded during the 4-min test period and the preceding 4-min rest period.

2.2.3. Subjective measures

Immediately following the final trial in each task condition, the subject was asked to rate the subjective tension and mental effort induced by the task, using visual analog scales. He or she placed a vertical mark on a 10-cm long horizontal line ranging from “little mental effort” (0 cm) to “considerable mental effort” (10 cm), and from “low subjective tension” (0 cm) to “high subjective tension” (10 cm).

2.2.4. Mental efficiency

Mental efficiency (E) was calculated according to the formula $E = (P - ME)/2$, using z-transformed perceived mental effort values (ME) and performance measures (P). According to this formula, mental efficiency is null when performance and mental effort z-scores are equal ($P = ME$), positive when performance scores are higher than mental effort scores, and negative when performance scores are lower than mental effort scores (Paas and van Merriënboer, 1993). This formula allowed controlling for the possibility that subjective ratings of effort might simply measure self-confidence or subjective comfort, rather than cognitive load (Kablan and Erden, 2007).

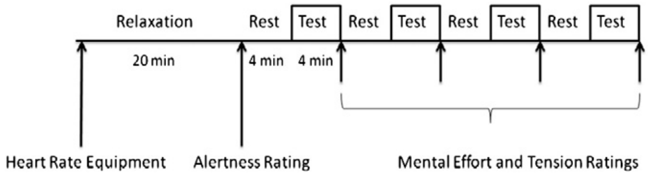

Fig. 1. Description of experimental procedure.

2.2.5. Subjective alertness

Each participant completed the French paper-and-pencil version of Thayer's Activation–Deactivation Adjective Checklist (Thayer, 1978), by selecting one of the following responses for each of 20 listed adjectives: “not at all”, “don't know”, “little” and “much”. These responses were weighted 1, 2, 3 and 4, but two of the adjectives were given negative weightings. The responses were totaled to yield four factors: general activation (GA), deactivation sleep (DS), high activation (HA), and general deactivation (GD). The GA/DS ratio yielded an alertness index.

2.3. Procedure

The procedure is described in Fig. 1. Each subject underwent two test sessions, performed between 9 am and 10 am, and between 4 pm and 5 pm respectively. The sessions were performed on the same weekday, separated by one week, starting with the morning session for half of the subjects. Once subjects have been informed of the aim of the study and general procedure, they were equipped with the S610i™, settled comfortably in an armchair and given a background questionnaire (age, gender, etc.) to fill in. Following a 20-min relaxation period, they were asked to complete Thayer's questionnaire. They then performed the computer task, with the instruction to respond as quickly and accurately as possible. Subjects were allowed to familiarize themselves with the task description and response procedures. After an additional 4-min rest period, the experiment started with the presentation of the first task condition. After they had completed the final trial in the first condition, participants rated mental effort and tension on the two scales. This marked the start of another 4-min rest period, and so on until the tasks in the three remaining conditions had been completed (Goodie et al., 2000).

2.4. Statistics

First, alertness scores for the different times of day were investigated by means of regression analyses. Thereafter, hierarchical linear multiple regression analyses tested the effects of task difficulty, time pressure, alertness, task difficulty × time pressure, task difficulty × alertness, time pressure × alertness, and difficulty × time pressure × alertness for each cognitive load measure. Data were analyzed according to the principle of parsimony, i.e., all factors were initially introduced into the regression model, and at each stage the factor with the lowest beta value was removed from the model, until a significant effect was obtained for all remaining factors. Moreover, as a significant difference was found between alertness in the morning and afternoon sessions, a separate multiple regression analysis was performed for each time of day, to test for the effects of task difficulty, time pressure, and difficulty × time pressure on the number of correct responses. Patterns of variations obtained for the different cognitive load measures were compared by performing Pearson's correlation test.

3. Results

A regression analysis of alertness scores on the different times of day revealed a significant effect ($\beta = .211$, $p = .021$), indicating that participants' self-rated alertness was higher in the afternoon than in the morning. Separate multiple regression analyses were then performed for each cognitive load measure.

Multiple regression analyses revealed that the number of correct responses was affected by alertness ($\beta = .19$, $p = .006$), and by task

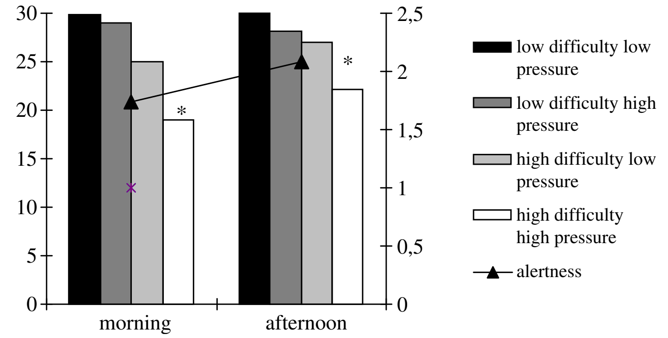

Fig. 2. Bars: number of correct responses in the morning and afternoon as a function of task difficulty and time pressure (left-hand scale). Line: alertness level in the morning and afternoon (right-hand scale). * $p<.05$.

difficulty × time pressure ($\beta = -.84$, $p = .005$). As indicated in Fig. 2, recall performance was lower when alertness was low, and when task difficulty and time pressure were both high. Differential heart rate was also affected by alertness ($\beta = .41$, $p<.001$), with more marked heart rate variations when self-reported alertness was high (Table 1).

Investigation of subjective load measures revealed a significant effect of task difficulty on subjects' self-reported cognitive effort ($\beta = .58$, $p = .001$), with higher task difficulty associated with higher perceived cognitive effort (see Table 2). No significant effect was obtained for perceived tension. Further, the mental efficiency index was significantly lower when alertness was low ($\beta = .17$, $p = .008$), and there was a significant interaction for task difficulty × time pressure ($\beta = -.55$, $p = .05$), with decreased mental efficiency when both task difficulty and time pressure were high (Fig. 3).

Moreover, separate multiple regression analyses performed separately on each test session revealed a significant effect of task difficulty × time pressure on the number of correct responses in the morning ($\beta = -.97$, $p = .017$), whereas there was no such effect on any measure in the afternoon.

Multiple correlations revealed that task performance and subjective load measures were negatively correlated with each other ($r = -.55$; $p<.001$, and $r = -.37$; $p<.001$), while no correlation was observed between either of these measures and differential heart rate. Thus, participants gave more correct responses when their perceived cognitive effort and tension were low, and vice-versa. In addition, the two subjective load measures were positively correlated with each other ($r = .52$, $p<.001$).

4. Discussion

Results of this study revealed both simple effects and interaction effects of mental workload factors in a working memory task. These effects will be discussed separately in line with cognitive load theory, as we believe that they reflect different processes, especially given that the intrinsic and extraneous load factors had limited effects when they were manipulated on their own.

Table 1
Heart rate variability (mean +/− *SD*) as a function of task difficulty, time pressure, and alertness ** $p<.001$.

		Mean heart rate variability	
Task difficulty	Low	2.29 (+/−5.14)	ns
	High	3.66 (+/−6.50)	
Time pressure	Low	1.87 (+/−5.68)	ns
	High	4.08 (+/−5.9)	
Alertness	Low	0.89 (+/−3.96)	**
	High	5.36 (+/−6.77)	

Table 2
Cognitive effort ratings (mean +/− *SD*) as a function of task difficulty, time pressure, and alertness ** $p<.001$. ns $p>.05$.

		Mean cognitive effort ratings	
Task difficulty	Low	3.71 (+/−2.16)	**
	High	6.71 (+/−2.10)	
Time pressure	Low	4.78 (+/−2.58)	ns
	High	5.64 (+/−2.59)	
Alertness	Low	5.53 (+/−2.61)	ns
	High	4.84 (+/−2.55)	

A first result indicates that manipulation of either intrinsic or extraneous cognitive load factors respectively by task difficulty and time pressure had little or no effect. Thus, task difficulty interfered only with participants' cognitive effort, which increased when task difficulty was high. Time pressure by itself had no significant effect on either load measure. In contrast, when time pressure and task difficulty were simultaneously high, both subjects' task performance and their mental efficiency decreased. These findings then suggest that the effects of a single load factor (intrinsic or extraneous) on one of the load measures (subjective or objective) may reflect some specific sensitivity of a given measure to this load factor. In contrast, interactions between intrinsic and extraneous load factors would indicate additive effects of these factors, further supporting the idea of a functional link between the cognitive load categories proposed by Sweller et al. (1998).

Interestingly, alertness interfered with all cognitive load measures used in the present study, as indicated by increased task performance and mental efficiency, and larger heart rate variations when subjects' alertness was high. These results then further extend the finding that variations in alertness, and therefore arousal, across the 24-hr day affect the amount of cognitive resources the subject needs to process items for immediate recall (Fabbri et al., 2007; Galy et al., 2008; Mélan et al., 2007). These results are generally interpreted as indicating that subjective measures and performance measures closely depend on the subject's functional state. As differential heart rate was also affected by alertness, the present results suggest that variables controlled by the autonomous nervous system may be good indicators of the cognitive resources available at the point of task completion. This may explain why Paas and van Merriënboer (1994b) concluded that heart rate variability was invalid, and insensitive to subtle mental load variations.

Further, cognitive effort was only sensitive to variations in task difficulty. This finding is in line with a recent review by Paas et al.

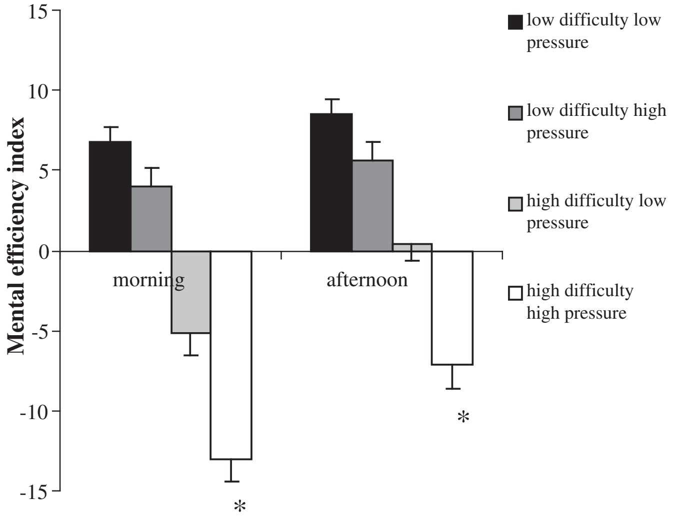

Fig. 3. Mental efficiency index as a function of task difficulty and time pressure in the morning and afternoon. * $p<.05$.

(2003a, 2003b) reporting the reliable sensitivity of subjective rating scales to relatively small differences in cognitive load (Gimino, 2002; Paas et al., 1994). As these studies mainly investigated intrinsic cognitive load effects by varying task difficulties, our findings are consistent with the idea that subjects are able to perceive differences in the cognitive effort they expend and to transcribe the corresponding sensation on a numerical scale. However, our results also indicate that subjective tools are less suitable for assessing mental workload variations resulting from task-independent factors.

As task performance was significantly affected by the combined effects of task difficulty and time pressure, as well as by alertness, this measure, and by extension the mental efficiency index, appeared to provide the most accurate assessment of total mental workload in the conditions of the present study. This raises the question of the mental workload components that were actually assessed by the different techniques used in the present study. If all measures had assessed the same mental load component, we should have observed a significant effect on each measure, even though the magnitude of the effect might have varied between the different categories of load measure. As this was not observed, further studies are needed to determine the best-suited tool in order to differentiate mental workload categories.

Although no interaction was found between alertness on one hand, and intrinsic and extraneous load factors on the other hand, the latter had a greater impact on task performance when participants' alertness was low than when it was high. When both task difficulty and time pressure were high, the number of correct responses was only lower in the morning, when cognitive resources were also reduced. No similar effect was observed in the afternoon, when cognitive resources are known to be enhanced (Galy et al., 2008). The performance decrement observed in the morning indicated that the cognitive resources allocated to working memory were taxed when participants' alertness was low, so that there were insufficient resources to perform the task efficiently.

The differential additive effect of task difficulty and time pressure according to alertness may therefore result from differences in the contribution of germane mental workload. When an easy task was administered to subjects under low time pressure, they did not need to use specific strategies to perform the task efficiently (Schnotz and Kürschner, 2007) even when alertness was low (in the morning) and the cognitive resources available in working memory were consequently more limited. In this condition, germane mental workload was virtually inexistent. On the other hand, performing the difficult version of the task under greater time pressure may have required subjects to use specific strategies, thereby generating germane load. Hence, the limited cognitive resources in the morning may have been entirely taken up by intrinsic and extraneous loads, leaving no resources to implement specific task strategies (germane load) required in this task condition. Conversely, with increased alertness in the afternoon, more cognitive resources could be allocated to working memory and subjects may then adopt the strategies needed to solve the task in the high difficulty and time pressure condition (high germane load).

Taken together, these results confirm the asymmetric nature of the relationship between germane load on one hand, and intrinsic and extraneous loads on the other (Schnotz and Kürschner, 2007). Germane load is determined by the subject's choice of strategies to be applied to the tasks experiment perform (as a function of alertness), whereas the implementation of these strategies is determined by the amount of free cognitive resources which, in turn, is determined by intrinsic load (task difficulty) and extraneous load (time pressure). From this point of view, alertness may be a germane load factor in the same way as task difficulty and time pressure. More specifically, alertness may determine the overall amount of cognitive resources that are available, whereas task difficulty and time pressure may determine the size of the mental load that is necessarily involved in performing the task (intrinsic plus extraneous load). The combined action of the latter determines the amount of capacity left for germane cognitive load. This conception implies that alertness and the other mental workload factors act on two different components of the cognitive system (see Fig. 4), which may account for the lack of an interaction effect for alertness and either other factor.

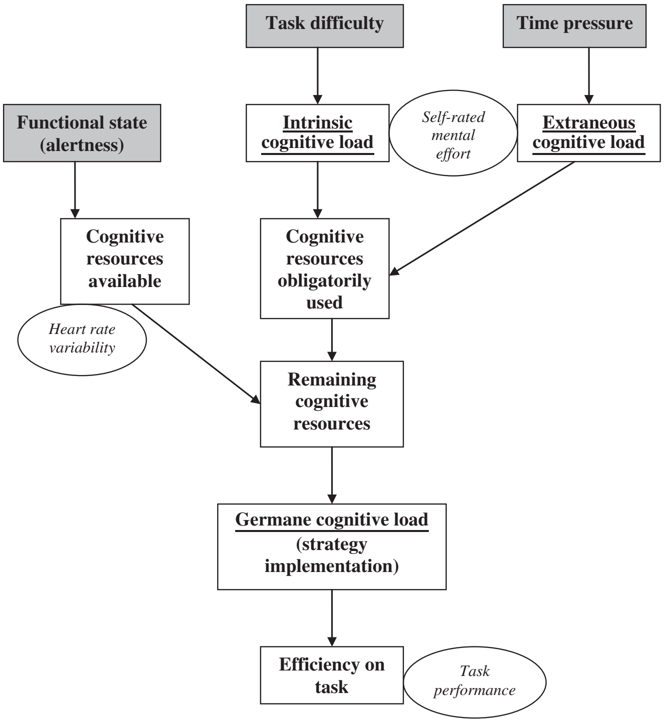

Fig. 4. Graphic representations of putative relationships between cognitive load factors and cognitive load categories.

5. Conclusion

To conclude, results obtained showed interest to address cognitive load theory in the field of ergonomics, and that consideration of three mental workload categories was important to understand sensitivity difference of measures to mental workload changes. Thus, the present study revealed the additive effects of task difficulty and time pressure in a working memory task, which explains why these factors are often cited in relation to wellbeing and safety issues at work. In addition, their combined action on mental workload measures was modulated by alertness, suggesting that it may be useful to consider the overall work situation, including work schedules, rather than focusing on specific task characteristics. Mental overload can be the result of a combination of task characteristics, such as time pressure and task difficulty, but its occurrence appears to depend on other characteristics, including alertness. As a consequence, solutions designed to reduce incidents and accidents at work must take organizational considerations (organization of staff and shift work) into account as well as more technical aspects.

References

Ayres, P., 2006. Using subjective measures to detect variations of intrinsic cognitive load within problems. Learning and Instruction 16, 389–400.

Backs, R.W., 1995. Going beyond heart rate: modes of autonomic control in the cardiovascular assessment of mental workload. The International Journal of Aviation Psychology 5, 25–48.

Backs, R.W., Seljos, K.A., 1994. Metabolic and cardiorespiratory measures of mental effort: the effects of level of difficulty in a working memory task. International Journal of Psychophysiology 16 (1), 57–68.

Boucsein, W., Ottmann, W., 1996. Psychophysiological stress effects from the combination of night-shift work and noise. Biological Psychology 42 (3), 301–322.

Brünken, R., Plass, J., Leutner, D., 2003. Direct measurement of cognitive load in multimedia learning. Educational Psychologist 38, 53–61.

Cariou, M., Galy, E., Mélan, C., 2008. Differential 24-h variations of alertness and subjective tension in process controllers: investigation of a relationship with body temperature and heart rate. Chronobiology International 25 (4), 597–607.

Carrol, D., Turner, J.R., Hellawell, J.C., 1986. Heart rate and oxygen consumption during active psychological challenge: the effects of level of difficulty. Psychophysiology 23, 174–181.

Chi, C.-F., Lin, F.T., 1997. A new method for describing search patterns and quantifying visual load using eye movement data. International Journal of Industrial Ergonomics 19 (3), 249–257.

Collet, C., Averty, P., Dittmar, A., 2009. Autonomic nervous system and subjective ratings of strain in air-traffic control. Applied Ergonomics 40, 23–39.

Docherty, P., Forslin, J., Shani, A., Kira, M., 2002. Emerging work systems: from intensive to sustainable. In: Docherty, P., Forslin, J., Shani, A. (Eds.), Creating Sustainable Work Systems. Emerging Perspectives and Practice. Routledge, London, pp. 3–14.

Fabbri, M., Natale, V., Adan, A., 2007. Effect of time of day on arithmetic fact retrieval in a number-matching task. Acta Psychologica 127 (2), 285–290.

Folkard, S., 1979. Times of day and level of processing. Memory and Cognition 7, 247–252.

Folkard, S., Knauth, P., Monk, T.H., Rutenfranz, J., 1976. The effect of memory load on the circadian variation in performance efficiency under a rapidly rotating shift system. Ergonomics 19, 479–488.

Folkard, S., Monk, T.H., 1980. Circadian rhythms in human memory. British Journal of Psychology 71, 295–307.

Fournier, L.R., Wilson, G.F., Swain, C.R., 1999. Electrophysiological, behavioral, and subjective indexes of workload when performing multiple tasks: manipulations of task difficulty and training. International Journal of Psychophysiology 31, 129–145.

Galy, E., Mélan, C., Cariou, M., 2008. Investigation of task performance variations according to task requirements and alertness across the 24-h day in shift workers. Ergonomics 51 (9), 1338–1351.

Gimino, A., 2002. Students' investment of mental effort. Paper Presented at the Annual Meeting of the American Educational Research Association, New Orleans, LA.

Goodie, J.L., Larkin, K.T., Schauss, S., 2000. Validation of the polar heart rate monitor for assessing heart rate during physical and mental stress. Journal of Psychophysiology 14, 159–164.

Gundel, A., Wilson, G.F., 1992. Topographical changes in the ongoing EEG related to the difficulty of mental tasks. Brain Topography 5, 17–25.

Hart, S.G., Staveland, L.E., 1988. Development of NASA-TLX (Task Load Index): results of empirical and theoretical research. In: Hancock, P.A., Meshkati, N. (Eds.), Human Mental Workload. Elsevier Science, Amsterdam, pp. 139–183.

Inzana, C.M., Driskell, J.E., Salas, E., Johnson, J.H., 1996. Effects of preparatory information on enhancing performance under stress. Journal of Applied Psychology 81 (4), 429–435.

Kablan, Z., Erden, M., 2007. Instructional efficiency of integrated and separated text with animated presentations in computer-based science instruction. Computers in Education 51, 660–668.

Kalyuga, S., Ayres, P., Chandler, P., Sweller, J., 2003. The expertise reversal effect. Educational Psychologist 38, 23–31.

Kirschner, P.A., 2002. Cognitive load theory: implications of cognitive load theory on design of learning. Learning and Instruction 12, 1–10.

Kompier, M.A.J., van den Berg, A.M., Aust, B., Siegrist, J., 2000. Stress prevention in bus drivers: evaluation of 13 natural experiments. Journal of Occupational Health Psychology 5, 11–31.

Koslowsky, M., Kluger, A.N., Reich, M., 1995. Commuting Stress: Causes, Effects, and Methods of Coping. Plenum, New York.

Mélan, C., Galy, E., Cariou, M., 2007. Mnemonic processing in air traffic controllers: effects of task parameters and work organization. The International Journal of Aviation Psychology 17 (4), 391–409.

Miyake, S., 2001. Multivariate workload evaluation combining physiological and subjective measures. International Journal of Psychophysiology 40 (3), 233–238.

Monk, T.H., Embrey, D.E., 1981. A field study of circadian rhythms in actual and interpolated task performance. In: Reinberg, A., et al. (Ed.), Night and Shift-work, Biological and Social Aspects. Pergamon Press, Oxford, pp. 473–480.

Monk, T.H., Leng, V.C., 1982. Time of day effects in simple repetitive tasks: some possible mechanisms. Acta Psychologica 5 (3), 207–222.

Monod, H., Kapitaniak, B., 1999. Ergonomie. Masson, Paris.

Mulder, G., Mulder, L.J.M., 1981. Information processing and cardio-vascular control. Psychophysiology 18, 392–405.

Paas, F.G.W.C., 1992. Training strategies for attaining transfer of problem solving skill in statistics: a cognitive load approach. Journal of Educational Psychology 84, 429–434.

Paas, F.G.W.C., Renkl, A., Sweller, J., 2003a. Cognitive load theory and instructional design: recent developments. Educational Psychologist 38 (1), 1–4.

Paas, F.G.W.C., Tuovinen, J.E., Tabbers, H., van Gerven, P.W.M., 2003b. Cognitive load measurement as a means to advance cognitive load theory. Educational Psychologist 38, 63–71.

Paas, F.G.W.C., van Merriënboer, J.J.G., 1993. The efficiency of instructional conditions: an approach to combine mental-effort and performance measures. Human Factors 35, 737–743.

Paas, F.G.W.C., van Merriënboer, J.J.G., 1994a. Instructional control of load measurement as a means to advance cognitive load theory. Educational Psychologist 6 (4), 351–371.

Paas, F.G.W.C., van Merriënboer, J.J.G., 1994b. Variability of worked examples and transfer of geometrical problem solving skills: a cognitive load approach. Journal of Educational Psychology 86, 122–133.

Paas, F.G.W.C., van Merriënboer, J.J.G., Adam, J.J., 1994. Measurement of cognitive load in instructional research. Perceptual and Motor Skills 79, 419–430.

Reid, G.B., Nygren, T.E., 1988. The subjective workload assessment technique: a scaling procedure for measuring mental workload. In: Hancock, P.A., Meshkati, N. (Eds.), Human Mental Workload. Elsevier Science Publisher B.V., Amsterdam, pp. 185–218.

Ritvanen, T., Louhevaara, V., Helin, P., Väisänen, S., Hänninen, O., 2006. Responses of the autonomic nervous system during periods of perceived high and low work stress in younger and older female teachers. Applied Ergonomics 37, 311–318.

Schnotz, W., Kürschner, C., 2007. A reconsideration of cognitive load theory. Educational Psychology Review 19, 469–508.

Seppälä, S., 2009. A proposal for a framework to evaluate feature relevance for terminographic definitions. 1st Workshop on Definition Extraction, Borovets, Bulgaria, September 18, pp. 47–53.

Sloan, R.P., Shapiro, P.A., Bagiella, E., Boni, S.M., Paik, M., Bigger, J.T., Gorman, J.M., 1994. Effect of mental stress throughout the day on cardiac autonomic control. Biological Psychology 37, 89–99.

Smit, A.S., Eling, P.A.T.M., Hopman, M.T., Coenen, A.M.L., 2005. Mental and physical effort affect vigilance differently. International Journal of Psychophysiology 57, 211–217.

Sweller, J., 1988. Cognitive load during problem solving: effects on learning. Cognitive Science 12, 257–285.

Sweller, J., 1994. Cognitive load theory, learning difficulty and instructional design. Learning and Instruction 4, 295–312.

Sweller, J., Chandler, P., 1994. Why some material is difficult to learn. Cognition and Instruction 12, 185–233.

Sweller, J., Van Merriënboer, J.J.G., Paas, F.G.W.C., 1998. Cognitive architecture and instructional design. Educational Psychology Review 10, 251–296.

Tattersall, A.J., Hockey, G.R., 1995. Level of operator control and changes in heart rate variability during simulated flight maintenance. Human Factors 37, 682–698.

Thayer, R.E., 1978. Toward a psychological theory of multidimensional activation (arousal). Motivation and Emotion 2, 1–34.

Wiebe, E.N., Roberts, E., Behrend, T.S., 2010. An examination of two mental workload measurement approaches to understanding multimedia learning. Computers in Human Behavior 26, 474–481.

Windell, D., Wiebe, E.N., 2007. Measuring cognitive load in multimedia instruction: a comparison of two intrusments. Paper Presented at the Annual Meeting of the American Educational Research Association.