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Effects of Cognitive Appraisal and Mental Workload Factors on Performance in an Arithmetic Task

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Abstract We showed in a previous study an additive interaction between intrinsic and extraneous cognitive loads and of participants' alertness in an 1-back working memory task. The interaction between intrinsic and extraneous cognitive loads was only observed when participants' alertness was low (i.e. in the morning). As alertness is known to reflect an individual's general functional state, we suggested that the working memory capacity available for germane cognitive load depends on a participant's functional state, in addition to intrinsic and extraneous loads induced by the task and task conditions. The relationships between the different load types and their assessment by specific load measures gave rise to a modified cognitive load model. The aim of the present study was to complete the model by determining to what extent and at what processing level an individual's characteristics intervene in order to implement efficient strategies in a working memory task. Therefore, the study explored participants' cognitive appraisal of the situation in addition to the load factors considered previously—task difficulty, time pressure and alertness. Each participant performed a mental arithmetic task in four different cognitive load conditions (crossover of two task difficulty conditions and of two time pressure conditions), both while their alertness was low (9 a.m.) and high (4 p.m.). Results confirmed an additive effect of task difficulty and time pressure, previously reported in the 1-back memory task, thereby lending further support to the modified cognitive load model. Further, in the high intrinsic and extraneous load condition, performance was reduced on the morning session (i.e. when alertness was low) on one hand, and in those participants' having a threat appraisal of the situation on the other hand. When these factors were included into the analysis, a performance drop occurred in the morning irrespective of cognitive appraisal, and with threat appraisal in the afternoon (i.e. high alertness). Taken together, these findings indicate that mental overload can be the result of a combination of subject-related characteristics, including alertness and cognitive appraisal, in addition to well-documented task-related components (intrinsic and extraneous load). As the factors investigated in the study are known to be critically involved in a number of real job-activities, the findings suggest that solutions designed to reduce incidents and accidents at work should consider the situation from a global perspective, including individual characteristics, task parameters, and work organization, rather than dealing with each factor separately.

Keywords Workload measures · Cognitive load · Time pressure · Task difficulty · Alertness · Cognitive appraisal · Arithmetic task

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Introduction

Since Miller's (1956) nominal paper suggesting that working memory capacity is limited to a defined number of digits of information, a central theoretical issue was to describe how people might organize information in a capacity-limited short-term memory store. Cognitive load theory (CLT) emphasizes the capacity limitations to process novel information in working memory in instructional or educational contexts, by distinguishing different load categories (Sweller 1988). "Intrinsic cognitive load" refers to the load induced by the material to be processed, such as task difficulty that is defined in particular by the number of items to be processed, and by item interactivity, and depends on the expertise of the learner (Ayres 2006; Kalyuga et al. 2003; Sweller and Chandler 1994). "Extraneous mental workload" refers to the components of a learning environment that may be modified to reduce total load, in particular by adequate instructions in a learning context, and by adapting the to-be-learned material in terms of its relevance, presentation format, adequate presentation of domain elements (Amadieu et al. 2009; Debue and van de Leemput 2014; Leppink et al. 2014; Merriënboer and Sweller 2010). Finally, "germane mental workload" corresponds to the load induced by conscious application of strategies to solve tasks more efficiently (Schnotz and Kürschner 2007).

Though CLT has been developed in the field of instructional design, a growing number of studies showed its usefulness in non-instructional designs, including e-learning (Amadieu et al. 2009; Debue and van de Leemput 2014; Leppink et al. 2014), clinical diagnosis (Durning et al. 2012) and ergonomics (Galy et al. 2012; Mélan and Cascino 2014). Though it is not yet clear to what extent cognitive load and workload refer to the same concept, the two latter studies revealed similar effects of three cognitive load factors in a controlled laboratory study and in field studies respectively. The relationships between these load factors and the load categories described by CLT, together with their assessment by specific load measures gave rise to a modified cognitive load model (Galy et al. 2012). In a 1-back working memory task, intrinsic load variations by task difficulty affected participants' perceived cognitive effort, thereby confirming that subjective load ratings are most sensitive to small load variations (Gimino 2002; Paas and van Merriënboer 1993, Paas et al. 2003). Simultaneous intrinsic and extraneous load (time pressure) variations were revealed by participants' performance and their mental efficiency (a measure computed from both, performance and self-rated effort, according to Paas and van Merriënboer 1993). Thus, in agreement with CLT (Sweller 1988) when the task was easy and/or had to be performed under low time pressure, it could be solved without requiring specific strategies (germane load virtually inexistent). Conversely, specific strategies, generating germane load, would have been required to solve the difficult task under high time pressure,. In agreement with de Jong's statement, we proposed that "intrinsic and extraneous cognitive load concern cognitive activities that must unavoidably be performed" (2010, p.113) and would represent the minimum cognitive resources that are required to solve a given task in a given context.

Further, effects of participants' alertness were revealed by differential heart rate, shown to provide systematic and reliable relationships with task demands and mental effort (Backs and Seljos 1994; Tattersall and Hockey 1995). Hence, in the 1-back memory task, the additive effect of task difficulty and time pressure was only observed when participants' alertness was low (i.e. in the morning), leading to the proposal that alertness may have determined the mental resources available for implementing specific strategies in working memory. More especially, limited cognitive working memory resources in the morning, as a consequence of low alertness, would have been insufficient to enable efficient strategies in the high difficulty/high time pressure conditions, while no effect was expected in the easy and/or low time pressure conditions as in these conditions the task could be solved without requiring specific strategies (germane load virtually inexistent). In other controlled laboratory studies, decreased alertness or arousal has also been shown to be associated with lower working memory performance (Fabbri et al. 2007; Smit et al. 2005), especially in the higher cognitive load condition (Jackson et al. 2014). Further, when the same load factors were explored in air traffic controllers performing a mental arithmetic task, time pressure improved performance in the low difficulty task condition, but only when controllers' alertness was high (Mélan and Cascino 2014). Resource theory also proposes that increasing task demands, fatigue or cognitive overload result in more resource consumption and this depletion of resources results in a vigilance decrement (Helton and Russell 2012). Accordingly, available mental resources that depend on an individual's functional state, together with the minimum resources necessary for intrinsic and extraneous load, would determine the amount of free processing resources that may be devoted to germane cognitive load and ultimately determine individual task efficiency, expressed by performance measures (Galy et al. 2012).

The purpose of the present study was two-fold: Testing in controlled laboratory conditions the modified cognitive load model in a different working memory task (i.e. a mental arithmetic task), and completing the model by including another factor known to affect cognitive load, i.e. individual characteristics. Before describing the study rationale in further detail, it may be useful to highlight that the load factors considered in the study have been reported to characterize job activity in a number of work situations. Accordingly, their combined investigation may provide a more contextualized application of CLT (de Jong 2010), also has been suggested for CLT for health professional education for instance (Merriënboer and Sweller 2010). In addition to the well-documented effects of work task difficulty in real-life settings, operating under time pressure figures among the major sources of stress in general (Matthews et al. 2013) and in safety-related job-situations in particular (for a review, Tucker and Folkard 2012). In work environments time may be part of a process that influences perception of control (Koslowsky et al. 1995), and short-term effects on brain and autonomous nervous system activity (increased heart rate) were reported in real and simulated work situations involving high tension and/or mental effort (Ritvanen et al. 2006; Sloan et al. 1994).

Further, the effects of certain cognitive load conditions at work, or of mental workload (i.e. overload but also underload), are most prominent on early morning hours or during the night, as indicated by a higher probability of an operator being involved in an accident or injuring himself at times when he/she would normally be asleep (Tucker and Folkard 2012). As stated by Akerstedt (2007, p. 209), three conditions that are typically associated with night- or shift-work, i.e. "being exposed to the circadian low, extended time awake, or reduced duration of sleep will impair performance". The short-term consequences of shift-scheduling systems on operators' cognitive performance and alertness, and thus on safety and security, and their long-term effects on physical and mental health are now well established (Costa 2010; Tucker and Folkard 2012). In shift-work conditions, alertness but also task-requirements appear to determine operators' task performance in a complex way (Mélan and Galy 2012). On early morning hours, when shift-workers' alertness was low, their performance dropped in various discrimination or memory tasks, but only in the more demanding task conditions, while no such effect was observed when alertness increased in the afternoon (Galy et al. 2008; Mélan et al. 2007; Mélan and Galy 2012). These results strongly favor the idea that low alertness is associated with low mental resources and increasing alertness with higher mental resources. In these studies, subjective alertness ratings enabled determining the circadian variations of an operator's functional state. Thus, Thayer's adjective check-list and visual analogue scale ratings have been shown to closely match the variations of a shift-workers' body temperature, which is known as a prominent marker of circadian rhythms (Cariou et al. 2008). These studies, together with the finding of positive relationships between alertness and performance with task difficulty and time pressure on one hand, and of these measures with low job demands and high job activity in real-job situations (Mélan and Cascino 2014), highlight time of day as a determinant factor of mental workload.

Elsewhere, in a recent formulation of CLT, Sweller (2010) stated that germane cognitive load is concerned only with learner characteristics. Several recent studies explored the role of various individual characteristics, either to further refine the definition of the different load types proposed by CLT or to point to the involvement of additional processes in selected CL tasks. Thus, disorientation, a psychological state induced by the difficulties during e-learning has been reported in participants with low prior knowledge (Amadieu et al. 2009), cognitive absorption or motivation during reading improved retention performance (Debue and van de Leemput 2014; Kuldas et al. 2014), and irrelevant contextual factors impacted on expert physician performance (Durning et al. 2012). Some earlier works already stressed the involvement of individual characteristics while implementing specific strategies in a cognitive task, including age, expertise (Schnotz and Kürschner 2007), and psychological processes, like stereotype threat (Steele 1997), and cognitive appraisal (Lazarus and Folkman 1984). "Stereotype threat" is a factor that inhibits stereotyped individuals to perform up to their full ability, and that occurs when a negative stereotype undermines performance of certain minority groups (Steele 1997 Working memory resources would be impaired (by three interrelated processes, i.e. a physiological stress response, self-monitoring of performance in order to find ways to restore the cognitive balance, and appraisal processes resulting in negative affect and cognition (for a review, Appel and Kronberger 2012; Schmader et al. 2008; Steele and Aronson 1995).

Folkman and Lazarus (1985) described for the first time the effects of cognitive appraisal on task performance. With a "challenge appraisal" participants were reported to be more heavily invested in task resolution (Saxby et al. 2013) and to display better performance than with a "threat appraisal". Tomaka et al. (1997) conceptualized threat and challenge responses as goal relevant multi-dimensional reactions in response to environmental demands. Threat appraisal has been shown to occur when the demands are perceived as taxing or exceeding the individual's resources and to be associated with negative affect and inadequate mobilization of physiological resources. In contrast, a challenge appraisal would occur when the demands are appraised within the person's resources, and is characterized by positive emotion and efficient physiological activation. In a mental arithmetic task, threat appraisals predicted greater negative affect and perceived stress, whereas challenge appraisals were related to greater positive affect and task engagement (Maier et al. 2003). Further, fatigue induced by cognitive overload has been shown to elevate appraisals of threat and uncontrollability (Saxby et al. 2013). Taken together, the data from the literature suggest that cognitive appraisal may be a determinant factor while implementing efficient strategies for solving a task accurately.

The present experiment was designed to test whether, and to what extent, cognitive appraisal would interfere with load types defined by CLT. Cognitive load measures were those described in previous studies (Galy et al. 2012; Mélan and Cascino 2014; task performance, cognitive effort self-ratings, differential heart rate, mental efficiency). We used a mental arithmetic task, sensitive to cognitive appraisal effects (Tomaka et al. 1997; Maier et al. 2003), and that may provide an indication of the participants' confidence in their ability to perform the task (Steele 1997). Visual analog scales enabled determining self-rated task-induced stress and resources to perform the task, and the ratio of both measures indicated participants' cognitive appraisal, as described by Tomaka et al. (1993).

In light of previous results, participants' performance was expected to be sensitive to all factors investigated. More especially, a simultaneous increase in task difficulty and time pressure would affect task performance in the morning (though not in the afternoon), and in those participants exhibiting a threat appraisal of the task (but not in those exhibiting a challenge appraisal). Despite comparable motivation and similar effort, underperformance with stereotype threat has been attributed to inefficient processing, as a result of negative affect and cognition, leaving only limited cognitive resources to perform efficiently (Steele and Aronson 1995). Though for different reasons, similar cognitive, affective and physiological consequences would characterize threat appraisal (Tomaka et al. 1997; Maier et al. 2003). Accordingly, in the present experiment, threat appraisal may be expected to affect cognitive load by reducing available resources that may be used for germane load, as has been shown previously for alertness (Galy et al. 2012). In contrast, participants with a challenge appraisal of their mental arithmetic abilities would allocate sufficient cognitive resources to perform the task, thereby promoting efficient task solving (Tomaka et al. 1993).

Methods

Participants

31 students ($M_{age} = 23.3$; $SD = 1.86$; range 20–27) volunteered to take part in the experiment. 18 participants (9 women and 9 men) studied biology and 13 studied psychology (6 women and 7 men). Participants attended two individual test sessions in the laboratory and abstained from drinking tea or coffee for three hours before the start of the tests. All participants gave their full informed consent before participating in the experiment that was performed in accordance with the Ethical Principles of Psychologists and Code of Conduct of The French Federation of Psychologists and Psychology and with the Ethical standards in chronobiological research (Touitou et al. 2006).

Material and Measures

Arithmetic Task

Each subject performed the task in four experimental conditions, defined by task difficulty and time pressure (low difficulty and low time pressure; low difficulty and high time pressure; high difficulty and low time pressure; high difficulty and high time pressure). Prolab was used for random item presentation and for response recording (latency and accuracy). Task difficulty was manipulated by requiring participants to add either 5 (low task difficulty) or 36 (high task difficulty) to a number displayed on the screen. Two- and three-digit items were selected so that the algebraic sum with 5 (low task difficulty) or 36 (high task difficulty) changed either the tenths or the hundredths in half of the 32 trials. In the two low time pressure conditions, there was no time limit, although participants were instructed to respond as quickly and accurately as possible. In the two high time pressure conditions, the time limit was set at 8000 ms. For each trial, participants entered the algebraic sum on a numeric keypad.

Differential Heart Rate

Changes in heart rate were recorded continuously throughout the experiment by an ambulatory heart rate (HR) monitor (Polar S610i^{TM}). These devices represent a convenient alternative to traditional electrocardiographs, as far as heart rate variability is concerned (Rezende Barbosa et al. 2014; Quintana et al. 2012). It is comprised of a transmitter worn around the chest and a receiver worn on the non-dominant wrist that stores the HR values. The HR values were then transferred over an infrared connection to a computer where they were subsequently analyzed using Polar Precision Performance Software. During measurements, participants 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, measures for differential heart rate were obtained between values of the 4-min test period and the corresponding baseline values of a 4-min rest period.

Subjective Measures

Immediately following the final trial in each task condition, the participant was asked to rate several visual analog scales. He/she indicated the mental effort induced by the task by 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). Cognitive appraisal was investigated following completion of each task condition, by using the procedure described by Tomaka et al. (1993). Primary evaluation and secondary evaluation were explored using 10-cm visual analog scales ranging from "little task-induced stress" to "considerable task-induced stress", and from "low resources to perform the task" to "high resources to perform the task" respectively. When the ratio of these measures was below the median value (cognitive resources higher than task-induced stress), the participant's cognitive evaluation was labeled "challenge appraisal", and when the ratio was above the median value (cognitive resources lower than task-induced stress), his/her cognitive evaluation was labeled "threat appraisal".

Mental Efficiency

Mental efficiency proposed by Paas and van Merriënboer (1993) was calculated using the formula $E = (P - ME)/2$, where P and ME corresponded to z-scores of performance and mental effort measures.

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 was used as an alertness index.

Procedure

Each participant performed each of the four task conditions between 9 and 10 a.m. and between 4 and 5 p.m. He/she was informed of the aim of the study before being equipped with the Polar monitor and was then asked to complete a background questionnaire (age, gender, etc.), and to rate the alertness checklist. Following 20′ of relaxation, they were given the task instructions ("you must respond as quickly and accurately as possible"), and an opportunity to familiarize themselves with the task procedure for approximately 2 min. Following a 4-min rest period, the experiment started with the administration of a randomly selected task condition, followed by subjective ratings including cognitive evaluation, and a rest period of 4 min. This procedure was repeated for the three remaining task conditions; each being preceded by a 4-min rest period.

Statistics

We first explored the effects of participants' gender and study field on the cognitive appraisal index, and alertness variations across the day with analyses of variance (ANOVAs). Thereafter, hierarchical regression analyses integrating difficulty, time pressure, alertness, task difficulty x time pressure, difficulty x alertness, time pressure x alertness, and difficulty x time pressure x alertness, and cognitive appraisal were performed according to the parsimony principle, on each load measure separately. Moreover, complementary analyses including intrinsic and extraneous load factors (task difficulty, time pressure, difficulty x time pressure) were conducted for each condition characterized as requiring low cognitive resources (morning session and/or threat appraisal) and for each condition requiring high cognitive resources (afternoon session and/or challenge appraisal).

Results

A first ANOVA, testing effects of gender and study domain (biology and psychology) on the cognitive appraisal index, revealed no significant effect indicating that variations observed fir this measure weren't induced by these factors. An ANOVA of time-of-day on alertness revealed that alertness was significantly lower in the morning than in the afternoon [$F(1,29) = 8.76$; $p = .004$, r^2 adj $= 0.06$]. Details of the analysis are presented in Table 1.

Hierarchical regression analysis on participants' performance (number of correct responses; Table 2) of all the factors considered in the study revealed a regression model with alertness, time pressure, task difficulty and time pressure x task difficulty explaining 81 % of variance of performance (r^2 adj $= .81$). A significant effect of alertness on performance ($\beta = .27$, $p = .04$) indicates that the number of correct responses increased with alertness, and a significant interaction between task difficulty and time pressure ($\beta = -1.55$, $p < .001$) revealed a performance decrement when task difficulty and time pressure were simultaneously increased (Fig. 1).

The same hierarchical regression analysis was conducted on perceived cognitive effort (Table 3), mental efficiency index (Table 4), perceived tension (Table 5), and on differential heart rate (Table 6). All factors were introduced into the analysis and after application of the parsimony principle, a model with difficulty, time pressure and difficulty x time pressure was obtained and explained

Table 1 Alertness as a function of time-of-day

	Alertness			
	Mean	Standard error	Confidence interval at 95 %	
			Inferior born	Superior born
Morning	1.087	.095	.899	1.276
Afternoon	1.480	.092	1.297	1.663
r^2 adjusted	.059			
	Time-of-day			
F	8.757			
Sig value	.004*			

Table 2 Number of correct responses as a function of difficulty, time pressure and alertness

Number of correct responses				Confidence interval to 95 %	
		Mean	Standard error	Inferior born	Superior born
Low difficulty	Low pressure	28.90	.36	28.17	29.57
	High pressure	25.30	.81	23.63	26.93
High difficulty	Low pressure	24.03	.81	22.47	25.60
	High pressure	7.23	.88	5.63	8.97
r^2 adjusted	.808				
	Difficulty	Time pressure	Difficulty X time pressure	Alertness	
β	.449	.517	−1.548	.272	
Sig value	.001*	.000*	.000*	.046*	

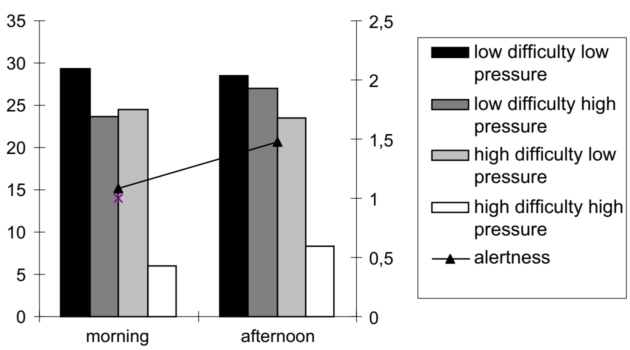

Fig. 1 *Bars* mean number of correct responses in the morning and in the afternoon as a function of task difficulty and time pressure (*left-hand scale*). *Line* Alertness level in the morning and afternoon (*right-hand scale*)

40 % of variance of perceived mental effort (r^2 adj = .40). A significant effect of interaction between task difficulty and time pressure was observed ($\beta = .55$, $p = .001$). Concerning mental efficiency, the same model than for perceived mental effort was obtained and explained 70 % of variance (r^2 adj = .70), and a significant effect of interaction between task difficulty and time pressure was too observed ($\beta = -.83$, $p = .001$). Moreover, a similar model was obtained for perceived tension explaining 21 % of variance (r^2 adj = .21) and revealing a significant interaction between both load factors (difficulty and time pressure; $\beta = .464$, $p = .001$). A similar analysis on differential heart rate revealed only a significant effect of alertness ($\beta = .35$, $p < .001$, r^2 adj = .11), indicating greater heart rate variations between the test and rest periods when participants' alertness was high.

Finally, complementary regression analyses were conducted on performance as a function of cognitive resources conditions. Thus, these analyses revealed variations of effect of interaction between task difficulty and time pressure according to cognitive resources conditions. Thus, this interaction affected the number of correct responses in the morning ($\beta = -1.48$, $p = .0001$, r^2 adj = .75), but not in the afternoon ($\beta = -.41$, *ns*, r^2 adj = .86). It also affected significantly more performance in participants with a "threat appraisal" ($\beta = -1.37$, $p = .002$, r^2 adj = .85) compared to those with a "challenge appraisal" ($\beta = -.56$, *ns*, r^2 adj = .79). When these two factors (cognitive appraisal and time of day) were considered, a significant interaction between task difficulty and time pressure reduced the number of correct responses in both "threat appraisal" ($\beta = -1.41$, $p = .0001$, r^2 adj = .78), and "challenge appraisal" participants ($\beta = -1.38$, $p = .0001$, r^2 adj = .72) in the morning, but only in "threat

Table 3 Perceived cognitive effort as a function of difficulty and time pressure

Perceived cognitive effort				Confidence interval to 95 %	
		Mean	Standard error	Inferior born	Superior born
Low difficulty	Low pressure	4.167	.498	3.187	5.135
	High pressure	5.423	.466	4.492	6.353
High difficulty	Low pressure	7.634	.288	7.030	8.192
	High pressure	8.661	.200	8.226	9.005
r^2 adjusted	.397				
	Difficulty	Time pressure	Difficulty X time pressure		
β	.604	.206	.553		
Sig value	.000*	.004*	.000*		

Table 4 Mental efficiency index as a function of difficulty and time pressure

Mental efficiency index				Confidence interval to 95 %	
		Mean	Standard error	Inferior born	Superior born
Low difficulty	Low pressure	.794	.086	.623	.965
	High pressure	.374	.086	.203	.545
High difficulty	Low pressure	−.080	.086	−.251	.091
	High pressure	−1.153	.086	−1.324	−.982
r^2 adjusted	.701				
	Difficulty	Time pressure	Difficulty X time pressure		
β	.135	−.129	−.825		
Sig value	.396	.419	.000*		

Table 5 Perceived tension as a function of difficulty and time pressure

Perceived tension				Confidence interval to 95 %	
		Mean	Standard error	Inferior born	Superior born
Low difficulty	Low pressure	3.681	.405	2.859	4.502
	High pressure	4.595	.415	3.774	5.417
High difficulty	Low pressure	5.415	.412	4.593	6.236
	High pressure	7.053	.409	6.232	7.875
r^2 adjusted	.209				
	Difficulty	Time pressure	Difficulty X time pressure		
β	.037	.195	.464		
Sig value	.885	.769	.000*		

appraisal" participants ($\beta = -1.54$, $p = .028$, r^2 adj $=$ .92) in the afternoon.

Correlations analyses between the different cognitive load measures revealed a significant negative relationship of task performance with perceived effort ($r = -.530$, $p < .001$), and perceived tension ($r = -.454$, $p < .001$), and a highly significant positive relationship of task performance with mental efficiency index ($r = .878$, $p < .001$). Moreover, each subjective measure was significantly correlated with each other (statistical details presented in Table 7). However, no significant relationship was observed between differential heart rate and any other measure.

Discussion

The present findings confirm and extend those reported in previous studies investigating the relationships between cognitive load factors and load types, by testing intrinsic

Table 6 Differential heart rate as a function of task difficulty, time pressure and alertness

Differential heart rate				Confidence interval to 95 %	
		Mean	Standard error	Inferior born	Superior born
Low difficulty	Low pressure	4.358	.748	3.030	5.914
	High pressure	6.099	.966	4.184	8.087
High difficulty	Low pressure	4.573	.792	3.154	6.306
	High pressure	4.286	.595	3.242	5.619
r^2 adjusted	.120				
	Difficulty	Time pressure	Difficulty X time pressure	Alertness	
β	.251	.422	−.495	.348	
Sig value	.359	.117	.182	.000*	

Table 7 Correlations between cognitive load measures

		Correct responses number	Perceived cognitive effort	Perceived tension	Differential heart rate	Mental efficiency index
Correct responses number	Pearson's correlation		−.530**	−.454**	0.086	.878**
	Sig. (bilateral)	1	0	0	0.351	0
Perceived cognitive effort	Pearson's correlation		1	.667**	−0.038	−.872**
	Sig. (bilateral)			0	0.672	0
Perceived tension	Pearson's correlation			1	.005	−.644**
	Sig. (bilateral)				0.955	0
Differential heart rate	Pearson's correlation				1	0.083
	Sig. (bilateral)					0.367
Mental efficiency index	Pearson's correlation					1
	Sig. (bilateral)					

** $p < .01$

load (task difficulty), extraneous load (time pressure) and individual characteristics (participants' alertness and cognitive appraisal). They raised several issues that will be discussed separately.

Interaction Between Intrinsic and Extraneous Cognitive Load Factors

The study revealed that a simultaneous increment in intrinsic and extraneous load by task difficulty and time pressure during task completion respectively, resulted into a performance decrement. This effect was observed in a mental arithmetic task in the present study and in a n-back memory task in a previous study (Galy et al. 2012). It was quite robust as it still occurred when additional factors were included into the analysis (see below), both in the present and the previous study. In both studies, additive effects of intrinsic and extraneous mental load also affected participants' mental efficiency index which was computed from task performance and self-rated effort. However, results of the two studies differed in that in the arithmetic task an interaction of task difficulty and time pressure was observed for self-rated cognitive effort, as for the aforementioned load measures, while in the n-back memory task a main effect of task difficulty occurred for this measure. In other words, participants would have perceived time pressure as a greater constraint when calculating the sum of two numbers than when retrieving numbers from short-term memory. This may be explained by the fact that the arithmetic task was cognitively more demanding than the memory task, given that in the former case participants had to manipulate the numbers in addition to maintaining them in the short-term buffer, whereas in the latter case they only had to maintain the numbers. It seems thus plausible to propose that participants would more rapidly gain the impression that they reached their cognitive limits with mental calculation.

Taken together, these results favor the hypothesis of a functional link between the two load categories, as suggested previously (Galy et al. 2012; Sweller et al. 1998). In line with these considerations, we argued that mental efficiency and self-estimated effort required to perform a task would provide reliable indications of the combined effects of the two load categories (Ayres 2006). There is, however, an ongoing debate concerning the measurement methods of the cognitive loads within CLT. Several authors stressed that multiple indicators of each cognitive load type would provide a broader evaluation of each load type than single items (Debue and van de Leemput 2014; Leppink et al. 2014). In this respect, multidimensional subjective rating scales have been developed, and self-ratings have been performed together with objective ratings, including performance measures, eye-tracking components and differential heart rate (Amadieu et al. 2009; Debue and van de Leemput 2014; Galy et al. 2012; Leppink et al. 2014; Smit et al. 2005).

In real-world settings, task load is not simply defined by task difficulty/complexity or item interactivity, but also by the perception of various dimensions of the environment, including physical, psychological and psychosocial aspects. Thus, assessing simultaneously various external and internal sources of load may enable determining the capacity that is left in working memory to implement efficient strategies to solve a particular task or a problem at work. Even though this methodology has been shown to be less specific than when each load type is assessed by different and multiple indicators, it may have an operational value in applied contexts. It is however noteworthy that "it is not entirely clear to what extent workload and cognitive load refer to the same concept across contexts" (Leppink et al. 2014, p.33). In safety-related job situations in particular, high demands or work overload have been found to be positively related to job strain and safety behavior (Li et al. 2013). In another study cognitive load in the arithmetic task described here was assessed together with air traffic controllers' job perception (job demands, control and social support), and control operations that were recorded following the psychological tests. Results revealed that controllers' performance in the high difficulty and high time pressure task conditions was associated with their real job activity and supervisor support (Mélan and Cascino 2014). Thus, assessing intrinsic and extraneous load with the same load measure may be informative in applied contexts when combined with more specific, job-related dimensions. Further, experimental paradigms like the one used in this study may be regarded as simplified models of real-job activities that involve similar cognitive processes. For instance, operating several flights at the same time or solving conflicts between aircrafts (intrinsic load) require air traffic controllers to make the right decisions under high time pressure and to give ground-to air instructions in a limited time (extraneous load; Mélan and Galy 2012).

Modulation of Cognitive Resources by Alertness

The second issue raised by the present study was the finding of a main effect of participants' alertness on task performance and differential heart rate. Both measures were specifically reduced when participants performed either working memory task in the morning, while their self-rated alertness was low (Galy et al. 2012). These results are in agreement for instance with the performance decrement reported when a number-matching task involving working memory was performed in the morning rather than later during the day (Fabbri et al. 2007). Likewise, a mental effort has been shown to be associated with decreased subjective alertness and increased theta power in the EEG, reflecting both an arousal decline (Smit et al. 2005). Interestingly, a physical effort induced a vigilance increment that was associated with higher subjective performance ratings but not with higher effective task performance. In contrast, in a driving simulation task, moderate cognitive load and moderate arousing motion improved participants' subsequent performance in various cognitive tasks, while these effects declined following either a low cognitive workload task or the absence of arousing motion (Jackson et al. 2014).

In line with these findings, the free working memory capacity that participants may have devoted to genuine load in the present study was proposed to be determined by both the minimal resources that were necessarily used to deal with intrinsic and extraneous load, as has been outlined above, and by individual's functional state, expressed by alertness and assessed by differential heart rate (Cariou et al. 2008). This is in agreement with the idea that ''mental load refers to the load that is imposed by task (environmental) demands. Mental effort refers to the amount of cognitive capacity or resources that is actually allocated to accommodate the task demands'' (Sweller et al. 1998, p. 266). According to de Jong (2010 p. 113), "germane cognitive load is the space that is left over that the learner can decide how to use, so this can be labelled as cognitive effort". This hypothesis was favored by studies investigating alertness effects on cognitive task performance by asking participants to perform a task at different times of day, either in controlled laboratory conditions or in field studies. In field studies, alertness variations may, however, depend on the job-situation considered and in particular on specific workload or on job demands (Mélan et al. 2007; Mélan and Cascino 2014). In the latter study for instance both air traffic controllers and satellite controllers reported higher alertness on shift-beginning rather than on later shift-phases, as a result of task organization across the shift. Further, the relation between alertness and task performance is not a simple linear relation, as time of day has been shown to interact with task load factors, including memory load, discrimination difficulty and presentation modality, suggesting that (Galy et al. 2008; Mélan et al. 2007). In other words, the entrainment of cognitive efficiency rhythms is driven by the circadian rhythm of arousal and is dependent on the amount of resources used to solve a task (Fabbri et al. 2007).

Further, when satellite controllers performed the arithmetic mental task while they were on duty, their alertness ratings were positively related to task performance (high extraneous load) on day-shifts and with self-rated cognitive effort during task completion on night-shifts. Conversely, high alertness was associated with low perceived job demands on day-shifts (physical demands), and on night-shifts (psychological demands). Further, both job activity (perceived job demands and real-job activity) and alertness were higher on day-shifts than on night-shifts. These data stress the need to consider shift-scheduling features, but also task organization within shifts when investigating workload in a given job-situation. This more especially as the consequences of reduced alertness in terms of safety and security in real-job situations are now well documented (Tucker and Folkard 2012). Findings of laboratory and field studies investigating cognitive load factors may also be accounted for by resource theory that posits that a performance decrement is due to resource demand, mental fatigue and cognitive overload (Helton and Russell 2012).

Cognitive Appraisal: Modulatory Effect on Cognitive Resources Versus Effect on Germane Load

Analysis of cognitive appraisal effects yielded similar effects than those described in the previous section for alertness. Task performance was only affected by a task difficulty x time pressure interaction in the morning (low alertness) but not in the afternoon (high alertness), and in those participants who had a “threat appraisal”, whilst not in those exhibiting a “challenge appraisal” in this situation. Even though the same effects were observed for the two factors, it is not clear from a theoretical point of view whether they intervened on the same processes, i.e. exerting their effects at the same level of the CL model. Strictly speaking, they would have somehow prevented efficient implementation of particular strategies, as their effects became apparent only in the high difficulty and time pressure condition, requiring the use of such strategies for high task performance.

This raises the possibility that cognitive appraisal may have decreased available cognitive resources that participants may have devoted for strategy implementation, as has been suggested in the previous section for alertness. According to Folkman and Lazarus (1985), cognitive appraisal determines participants’ task investment and the use of available cognitive resources for additional strategic cognitive processing. Engagement has been reported to correlate with challenge appraisal, high task focus and positive affect (Maier et al. 2003; Matthews et al. 2013). The present study, the combined effects of intrinsic and extraneous load on cognitive appraisal may be explained by lower task investment in those participants with a “threat appraisal” compared to those with a “challenge appraisal”. Accordingly, the latter would have been able to use more appropriate strategies as a result of their task investment, in particular in the more demanding task condition. From this point of view, cognitive appraisal played a similar role than alertness in the present experiment, and determined an individual’s cognitive resources available for germane load, once the minimal resources (i.e. intrinsic and extraneous load) have been subtracted. If this was indeed the case, it is tempting to speculate that the modulatory effect of cognitive appraisal on cognitive resources were mediated by processes that are not under participants’ conscious control, as is the case for alertness that is controlled by endogenous mechanisms. The influence of learner motivation, involving both conscious and unconscious processes, could be a good candidate for mediating these effects. The role of learner motivation in CLT (Moreno and Mayer 2007) has been neglected until recently (for a review, see Kuldas et al. 2014), despite the fact that an individual’s motivation is certainly a key process in learning and performance. Sweller (2010) proposed that germane load could be related to individual characteristics, i.e. to learner motivation and may reflect the cognitive resources devoted to dealing with the to-be-learned material. Debue and van de Leemput (2014) found that germane load was positively associated with several dimensions of cognitive absorption, representing a measure of user motivation.

Alternatively, it may be argued that threat appraisal would act directly on the implementation of efficient strategies, independently of cognitive resources. The multiple effects of a threat response, and in particular the negative affect (Maier et al. 2003; Matthews et al. 2013) may indeed hamper participants’ to apply adequate strategies to solve the task, as the result of either a loss of control, motivation or allocation of effort or attention (Debue and van de Leemput 2014; Kuldas et al. 2014; Moreno and Mayer 2007).

Recent evidence from the literature suggests that cognitive appraisal of the situation may have directly interfered with implementation of specific task strategies, rather than indirectly by diminishing overall resources available for germane load. As a threat response is associated with negative affect (Maier et al. 2003; Tomaka et al. 1997), it may generate task-irrelevant affective and/or cognitive processing (for a review, Kuldas et al. 2014). Negative emotions may for instance bring about task-irrelevant thoughts that are retrieved from long term-memory probably at the same time as numerical facts required for solving the present task. Alternatively, when information is perceived as frustrating or aversive, learners would exert no more cognitive effort for processing the information, in particular when demanding mental math skills are necessary, and this even more when performing under time pressure. Inhibitory effects of negative emotions may also emerge when learners make a conscious effort to avoid failures while solving a task. Likewise, attempts to suppress stereotype-related thoughts generate anxiety and narrow participants' attention, thereby consuming cognitive resources that are unavailable for task performance (Steele and Aronson 1995). More recent studies suggested that in such a context several processes would impair working memory resources which are necessary for test taking. Physiological stress and inadequate arousal would directly impair processing. Monitoring performance to restore the cognitive balance would both elicit appraisal processes resulting in negative affect and cognitions. These processes and subsequent efforts to suppress negative thoughts and emotions would consume cognitive resources that are unavailable for the to-be-performed task (Schmader et al. 2008; Appel and Kronberger 2012).

From the above considerations it is clear that the affective and/or cognitive processes potentially activated by threat appraisal are not relevant to the to-be-performed task. For this reason, Kuldas et al. (2014, p. 365) consider that "cognitive load as task-irrelevant thoughts associated with negative emotions need to be distinguished from the intrinsic and extraneous load". Accordingly, irrelevant thoughts and emotions may directly impact on, or interfere with, the implementation of mental calculation strategies. According to these considerations, effects of alertness and cognitive appraisal would involve different pathways and act at different levels of the CL model. Cognitive appraisal would act on a cognitive level, because the thoughts, though irrelevant, generate cognitive load that would hamper strategy implementation required for the task to be performed. In other words, the load induced by cognitive appraisal would be the result of superfluous processes that do not directly contribute to learning. As this is precisely the definition of extraneous load in CLT (Sweller 2010) it may be considered as extraneous load. Instead, alertness would intervene at a non-cognitive level, and would reduce available cognitive resources in a nonspecific manner, as suggested in the present study by its effects on a psychophysiological measure.

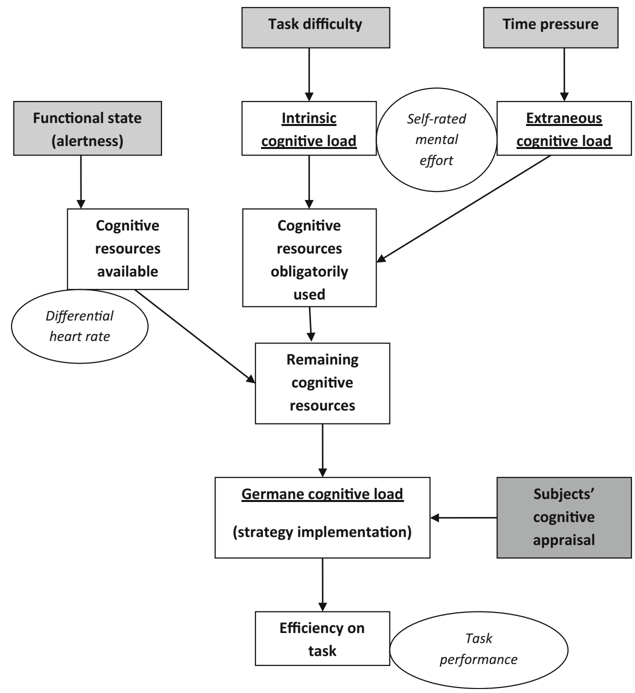

Fig. 2 Graphical representations of putative relationships between cognitive load factors and cognitive load categories

Conclusion

The present findings lend further support to the model illustrated on Fig. 2. Briefly, alertness may have determined overall cognitive resources available, whereas task difficulty and time pressure would have determined the cognitive load necessarily involved while solving the task (intrinsic plus extraneous load). The combined action of these factors would determine the remaining cognitive resources that can be used for germane cognitive load and execution of appropriated strategies. This vision implies that alertness and other cognitive load factors would act on two different components of the cognitive system confirming the asymmetric nature of the relationship between germane load on one hand, and intrinsic and extraneous loads on the other (Schnotz and Kürschner 2007), and explaining the absence of an interaction between alertness and task difficulty or time pressure. As task performance varied with alertness, task difficulty, and time pressure, this load measure would be most sensitive to variations of total load. The remaining measures used in the study were sensitive to task difficulty and time pressure, suggesting that they assessed mainly intrinsic and extraneous mental workload. The latter measures were also sensitive to alertness variations what is not surprising given that alertness variations are associated with task performance variations in difficult task conditions (Galy et al. 2008; Mélan et al. 2007; Mélan and Galy 2012; Mélan and Cascino 2014; Smit et al. 2005).

Cognitive appraisal would also determine germane load, by acting either on overall resources available, like alertness, or by interfering directly with strategy implementation. The results did not allow deciding which explanation is the most likely, as alertness and cognitive appraisal effects were similar. Given that intrinsic and extraneous load only affected performance in participants with a threat appraisal, cognitive appraisal may specifically affect the ability to implement additional strategies. This would also account for the observation that cognitive appraisal did not interact with alertness, so that cognitive appraisal may act on the third level (represented in Fig. 2). Further studies are necessary to test this hypothesis and the idea that cognitive appraisal and alertness act via different pathways. For instance, investigating task-unrelated thoughts by a specific questionnaire (Helton and Russell 2012), should thus reveal whether such thoughts are more frequent in participants with a threat appraisal than in those exhibiting a challenge appraisal. Further, in line with the motivation hypothesis, encouraging participants may increase their self-confidence and thereby decrease threat appraisal.

Compliance with Ethical Standards

Author Contributions EG and CM made equivalent contributions to the different aspects of the present work and are both considered first author.

Conflict of interest The authors declare that the research was conducted in the absence of any commercial or financial relationship that could be construed as a potential conflict of interest.

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