Psychophysiological Processes of Mental Effort Investment

Stephen H Fairclough

School of Natural Sciences and Psychology,

Liverpool John Moores University, UK

L J M Mulder

Department of Psychology,

University of Groningen, The Netherlands

Author for Correspondence:

Dr. Stephen Fairclough

School of Natural Sciences and Psychology,

Liverpool John Moores University

Tom Reilly Building, Liverpool.

s.fairclough@ljmu.ac.uk

TEL: + 44 (0)151 2314199

FAX: + 44 (0)151 2314243

1. Background

There is general agreement that stress, fatigue and mental workload exert significant influence on the quality of human performance (Hancock & Desmond, 2001). Research into this triad is united by the need to understand and predict changes in performance under conditions of challenge or duress. The appraisal of threat and derivation of compensatory strategies to protect performance is described by a dynamic cycle of behavioural adaptation (Hancock & Warm, 1989). A model of this process was proposed by Hockey (1993, 1997) wherein an upper executive was associated with a controlled, effortful mode of cognitive processing that was slow but capable of dealing with novelty and uncertainty. This upper loop is related to compensatory effort and processes of goal-setting. By contrast, the lower performance loop was responsible for effort investment into task-specific cognitive demand, i.e. task-related effort.

This process of effort regulation is fundamental to the study of stress, fatigue and mental workload. All three states constitute potential threats to performance quality and psychological wellbeing. All three provoke cycles of appraisal and adaptation to protect performance and preserve the personal goals of the individual. The main proposition of the current chapter is that mental workload, stress and fatigue engage a common mechanism of effortful adaptation to: (a) preserve the quality of performance, and (b) protect the personal goals of the individual.

The trigger for mental effort investment has been described as cognitive or compensatory in nature (Mulder, 1986). In the case of the former, mental effort is invested in response to changing task demands, e.g. increased working memory load. Compensatory mental effort is important to protect performance under demanding conditions, such as sustained task activity, or extraneous biological stressors, e.g. sleep deprivation, drugs. In both cases, mental effort investment represents an adaptation to external or internal stimuli. This adaptive facility of effort may be better understood in relation to four central hypotheses (Pashler, 1998) that encapsulate core themes associated with mental effort derived from different theoretical traditions.

1. The investment of mental effort will improve or sustain the quality of cognitive performance.

This first hypothesis is obvious - however, there are many situations where effort and performance are not closely related to one another. This distinction was captured by Eysenck (1997) who characterised the efficiency of performance as the relationship between covert effort investment and overt performance quality.

2. There are finite limits on mental effort investment.

This hypothesis is derived from resource theory (Kahneman, 1973) and it takes one of two forms. One hypothesis states that finite mental effort may only be hared between concurrent activities in a limited fashion dependent on input modalities, sensory codes and outputs (Wickens, 2002). The second form concerns finite limitations on effort investment with respect to time, such as vigilance tasks (Davies & Parasuraman, 1982).

3. Mental effort investment is associated with costs.

The investment of mental effort is coupled to changes in Central Nervous System (CNS) activity and associated variables such as subjective mood. These changes have been characterised as "costs" to the individual (Hockey, 1993; 1997). Concurrent costs represent instantaneous changes in mood and CNS activity that occur as a direct consequence of performance, see also the mood-behaviour model (Gendolla, 2000) for a similar concept.

4. The investment of mental effort is associated with volition

The purpose of effort investment (in a narrow sense) is the attainment and maintenance of task goals that are inherently desirable, such as "good" performance, i.e. low error frequency, efficient task completion etc. In this sense effort has strong ties to broad constructs such as willpower (James, 1890), volition (Baars, 1993), goal-regulation (Locke & Latham, 1990) and potential motivation (Brehm & Self, 1989).

These four hypotheses encapsulate an adaptive mechanism of mental effort that responds to increased workload, fatigue or stress. This mechanism is associated with volition, changes in mood and may only be deployed for a limited period of time.

2. The Process of Mental Effort Investment

The process of mental effort investment may be identified with energy expenditure at cerebral sites. This connection is simplistic (Beatty, 1986) but also intuitive as the brain requires a continuous supply of glucose and oxygen via the bloodstream. Both are required to generate adenosine triphosphate (ATP), which acts as the primary source of cellular energy at cerebral sites; in addition, the energy requirements of the brain are considerable, accounting for approximately 20-30% of the body's resting metabolic rate (Saravini, 1999). Despite these high requirements, the brain has only a limited capacity to store energy substrates and cerebral metabolism is dependent on the supply of glucose and oxygen from the bloodstream. The process of mental effort investment may be identified with catabolic activity at cerebral sites or with the transport of energy substrates to the brain.

The process of energy transport to the brain has been studied directly via the use of Transcranial Doppler sonography (TCD) to monitor blood velocity in the middle cerebral artery (MCD); changes in blood flow have been associated with both vigilance performance over sustained periods only (Helton, et al., 2007; Warm & Parasuraman, 2007) and with changes in EEG activity (Szirmai, Amrein, Palvolgyi, Debreczeni, & Kamondi, 2005). With respect to measuring energy substrates directly, there is evidence that raised glucose levels (via ingestion) enhanced cognitive performance for effortful tasks but not for tasks that were less demanding, e.g. a glucose drink improved performance on a serial sevens task but not a serial threes task (Kennedy & Scholey, 2000). Similarly, when participants performed either a demanding or an easy version of the Stroop task over forty minutes, blood glucose levels fell at a higher rate during an effortful task relative to an effortless activity (Fairclough & Houston, 2004). The following sections will focus on changes associated with mental effort investment at cerebral sites (electrocortical activation) and autonomic modes of energy mobilisation that influence the cardiovascular system.

The use of neuroimaging techniques, such as positron emission topography (PET) and functional magnetic resonance imaging (fMRI), have made the measurement of energy consumption the norm in cognitive neuroscience research, e.g. Cabeza & Nyberg (2000). With respect to brain areas and circuits associated with mental effort, meta-analyses of the n-back working memory paradigm (an effortful activity) identified robust activation over a number of regions, particularly the dorsolateral and ventrolateral prefrontal cortex as well as the medial and lateral posterior parietal cortex (Owen, McMillan, Laird, & Bullmore, 2005).

Early research on EEG activity and mental effort indicated that high levels of visual demand reduced alpha from parietal and occipital locations whilst augmenting theta activity in left frontal areas (Gundel & Wilson, 1992). The source of the frontal midline theta rhythm has been localised to the anterior cingulate cortex (ACC) (Gevins, et al., 1997) and the bilateral medial prefrontal cortex (Ishii, et al., 1999). These findings were replicated in further studies with respect to levels of working memory load (Gevins, et al., 1998) and the effects of practice on effortful performance (Smith, McEvoy, & Gevins, 1999). The same pattern of theta augmentation at frontal midline sites and alpha suppression in occipital areas was apparent using applied tasks such as operating the Multi Attribute Test Battery (MATB), i.e. a simulation of multi-tasking in an aviation environment (Smith, Gevins, Brown, Karnik, & Du, 2001). This pattern of EEG activity may be characteristic of task-related mental effort investment. Interested readers are advised to read available summaries of this research (Gevins & Smith, 2003, 2006).

3. Mental effort and the cardiovascular system

As described in section one, mental effort may be invested in response to task-related changes such as increased cognitive complexity (computational effort) and to protect performance when the person is fatigued (compensatory effort) (Mulder, 1986). It is argued that both categories of effort investment have specific effects on the cardiovascular system. When mental effort is invested, there are a number of characteristic changes in the cardiovascular system, such as increased heart rate (HR) and blood pressure (BP) in combination with a more regular heart rate (i.e. decreased heart rate variability, HRV). This pattern is associated with the investment of computational effort in response to increased task difficulty (i.e. increased mental workload). In those cases where effort is invested to compensate for a non-optimal physiological state (e.g. fatigue), cardiovascular state changes are less consistent and strongly dependent on the specifics of the state (e.g. stress, fatigue, sustained performance, sleep deprivation). This depends mainly on the individuals' response pattern related to short-term blood pressure control (baroreflex).

Autonomic activation influences heart rate and other effector sub-systems of short-term blood pressure control, such as: contraction force of the heart, (peripheral) resistance of the arteries, filling of the large veins of the body (venous volume, venous return to the heart). All these sub-systems work in concert to control heart function and levels of blood pressure in order to optimise performance for the present mental state (i.e. to provide appropriate energetical resources to the brain). The level of blood pressure is monitored by baroreceptors in the large body arteries (Karemaker, 1987) and these receptors provide information to a specific 'team of nuclei' in the brainstem that could be considered to be the cardiovascular control centre; members of this team include: the nucleus tractus solitarius (NTS, integration of incoming information), nucleus ambiguous (NA, vagal control) and the rostral ventrolateral medulla (RVLM, sympathetic control). Sympathetic activation is further supported by motor neurons situated in the intermediolateral cell column (IML) of the spine. This complete sub-system is crucial in the regulation of sympathetic and parasympathetic activation to the heart and encompasses the negative feedback loop of the baroreflex (see Figure 1).

INSERT FIGURE 1 HERE

Figure 1. Mechanisms of short-term blood pressure control

In order to achieve effective cybernetic control it is important to know that BP (and not, for instance, blood supply to the brain) is the controlled variable in this system. This category of BP control is achieved via the baroreflex (Julius, 1988, Guyton, 1980). Therefore, we may expect that observed changes in one effector sub-system, such as heart rate, have a function in relation to the control of short-term blood pressure. During periods of task-related effort investment, heart rate will be influenced by the activity of cortical centres that project to NA, RVLM, IML, NTS or related areas in the limbic system and higher brain areas, such as: the anterior cingulate cortex (ACC), the hypothalamic area, the locus coeruleus (LC), the amygdalae and the prefrontal cortex (PFC). The latter group serves a main function in regulating state control, emotional functioning, general activation of brain and body and task performance (e.g. decision-making, planning). The equilibrium between these state-regulating mechanisms for blood pressure control and task-related autonomic activity determines the precise pattern of cardiovascular responses that is observed during mental effort investment.

This description begs a question regarding the relationship between heart rate variability (HRV) and these regulating mechanisms in the brain. A main source of HRV is the so-called 10 second or Mayer-Hering rhythm (0.1Hz component) which amplitude decreases during mental effort investment (Mulder & Mulder, 1981). Wesseling & Settels (1985) used a simulation model of the baroreflex to demonstrate that this rhythmicity can be seen as an 'eigenrhythm' of the baroreflex and that it explains more than half of HRV. The frequency of this rhythm is determined by a combination of time constants and time delays in the effector systems described in Figure 1. Van Roon et al. (2004) extended this model to demonstrate that the magnitudes of these waves were strongly determined by the level and balance of autonomic activation. For instance, a 50% reduction of HRV in this frequency range (which is typical of increased computational effort) can be explained by a combination of vagal inhibition (about 40%) and increased sympathetic activation (about 25%).

Changes in blood pressure control are not the only way to influence the pattern of HRV during mental effort investment. Respiratory sinus arrhythmia (RSA) is another source of HRV that is related to respiration. During inspiration heart rate increases and returns to the previous level at the end of expiration (Grossman & Taylor, 2007). The main factor underlying these changes is vagal inhibition: during inspiration a vagal reduction of approximately 30% occurs. In general, respiratory frequency (i.e. breathing rate) is between 9 and 21 cycles per minute (0.15 Hz – 0.35 Hz); this means that in many cases RSA is well-separated from the 0.10 Hz rhythm. However, this does not hold for situations such as strong relaxation or meditation where breathing rate can come down to the frequency region of the 0.10 Hz rhythm (6 cycles per minute). In this case, a kind of synchronisation occurs between both rhythms called entrainment. The RSA magnitude is dependent on both respiratory depth and frequency (Grossman & Taylor, 2007). The level of RSA is highest when breathing rate is around 0.10 Hz, while it decreases continuously to about 30% of this level at about 0.40 Hz. RSA is also larger with deeper respiration than with more superficial breathing and the difference in magnitude can be large, about around a factor of two during normal respiration (Angelone & Coulter, 1964; Hirsh and Bishop, 1981). Knowing that the sympathetic system is too slow to induce HRV changes in a frequency area higher than 0.15 Hz, HRV reductions during task performance in this area are considered to be related to vagal inhibition (Saul et al., 1991). A third source of HRV can be found in the lower frequency range, roughly below 0.06 Hz. HRV fluctuations in this range are supposed to be related to either slow adaptations to the task demands or body temperature changes. Although connections with sympathetic activation can be expected, origins of HRV changes in this frequency area are too variable in general to be useful in experimental research (Mulder & Mulder, 1981).

HRV indices can be derived either in the time or the frequency domain. Time domain measures are based on the durations of cardiac intervals (IBI, interbeat interval times) and include standard deviations (or variance) as well as succeeding differences in IBI's (Berntson et al., 1997). Frequency domain measures, i.e. the power in several frequency bands, can either be based on IBI-sequences or on heart rate (HR) variations. Spectral measures have the advantage that results can be better connected to underlying physiological mechanisms than time domain measures. IBI spectra, in general, are obtained by using Fast Fourier Transform (FFT) algorithms, while HR spectra are obtained by applying a Discrete Fourier Analysis algorithm (DFT, Rompelman, 1980). The choice whether to choose for IBI or HR measures is dependent on both practical and theoretical arguments (Rompelman, 1980). It must be realised that IBI-based and HR-based variability measures do not give the same results, unless normalisation to the mean is applied (Akselrod et al., 1981; Mulder, 1992). If such a normalisation is not applied, spectral HRV measures are heavily dependent on mean HR in the analysis segment at hand (Stuiver & Mulder, 2009).

The spectral bands that are used for both HRV and other cardiovascular measures are dependent on the field of application (mental effort vs medical/physiological/stress research) and on historical habits. In general, either Low (0.02 – 0.06 Hz), Mid (0.07 – 0.14 Hz) and High (0.15-0.40 Hz) frequency bands are used (Mulder, 1992) or LF (0.04 – 0.14) and HF (0.15- 0.40) frequency bands (Pagani et al., 1992). In addition, a spectral band around the mean respiration frequency may be applied in special cases (Mulder, 1992). In general terms, HR increases and becomes more regular during mentally demanding performance compared to resting measurements and/or easy tasks, i.e. heart rate variability (HRV) decreases as a function of invested mental effort. HRV herein is defined as the series of the beat-to-beat changes in time duration between successive heart beats (IBI, Interbeat Interval Time) or the equivalent changes in HR. Several authors have shown the strong effects of mental effort investment on HRV, in particular for tasks in which working memory is heavily involved, such as mental arithmetic, memory search and counting, or planning (Aasman et al., 1987; Kramer, 1991, Mulder & Mulder, 1981, Veltman & Gaillard, 1993). All these authors indicate that the mid frequency band is most sensitive to manipulations of task load, while the pattern of changes is about the same for the other two frequency bands (Low, High/RSA). Most of these results were confirmed over short periods (e.g. about 5 minutes) in laboratory tasks. (Veltman & Gaillard, 1998) indicated that differences in both HR and HRV measures in most cases are not consistent (or not large) enough to distinguish different levels of task load. This may be related to the sensitivity of these measures but is also connected to the fact that participants are not always motivated to perform tasks at a maximum level; therefore, they can regulate their effort investment over a wide range when conducting well defined laboratory tasks without showing a significant decrease in task performance (De Waard,1996; Hockey et al, 1997).

Although the HRV rest-task effect in the mid frequency band is fairly strong in the majority of participants, this effect may be magnified by increased breathing rhythm during task performance. This factor is particularly apparent when participants are breathing quite slowly (slower than 8 or 9 cycles per minute) during rest in comparison to faster breathing rates (e.g. > 9 cycles per minute) during task performance. During rest, breathing rate is within the mid frequency range in such cases, while it is in the high frequency band during task performance (Althaus et al, 1998; Grossman & Taylor, 2007). However, Mulder & Mulder (1981) emphasised that the mid frequency band is most suitable index of mental effort because it is less affected by respiration than the high frequency band. Some authors have proposed methods for (statistically) separating breathing related HRV (=RSA) from other heart rate fluctuations (Althaus et al., 1998; Berntson et al., 2007; Grossman & Taylor, 2007). The methods indicate that it is very relevant to pay more attention to the interaction between effort related effects on HRV and breathing related effects. This holds in particular when respiration rate is at boundaries of the defined frequency bands (mid and high band), or when respiration rate (and amplitude) is strongly different between conditions. It should be realised, however, that any change in respiratory pattern is not just a 'mechanical' phenomenon; it is a relevant indication of a changed physiological state during task performance. In this respect it is very helpful to use measures of respiration frequency and depth and, if possible, a respiration related frequency band of HRV in research on mental effort investment (Grossman & Taylor, 2007).

Aside from laboratory tasks, HRV is also applied in numerous workload studies in different applied situations. Effects of mental effort changes are difficult to study in daily working environments because of the enormous variations in mental work. In studies on simulated and real mental work (driving, flying, ATC), significant results are found of decreased HRV in the mid frequency band with increasing levels of task complexity (DeRivecourt et al., 2007; De Waard et al., 2008; Veltman & Gaillard, 1996; Wilson & Fischer, 1991). Although finger BP and respiration changes (amplitude and frequency) are applied only occasionally in comparison to HR and HRV measurement, clear results have also been found in these measures, both in laboratory and simulated workload applications (Mulder et al., 2003). The overall cardiovascular pattern found can be characterised by increased BP, HR and breathing frequency and decreased HRV, blood pressure variability, baroreflex sensitivity and breathing amplitude. Some authors have described this general pattern as a defensive reaction type (Mulder et al., 2009).

The other aspect of effort investment is related to compensatory mechanisms when an operator is in a less than optimal physiological state, for instance after sleep deprivation or while being seriously fatigued after a long working day (Myles & Romet, 1987; Myrtek et al., 1994). In such situations an operator must put additional effort in the task in order to counteract the deleterious effects of fatigue on performance. Experimental cardiovascular effects related to this aspect of effort investment are far less clear than those on task related effort (Hockey et al., 1997). It is obvious that not only HR or HRV is relevant to compensatory effort but that cardiovascular regulation has to be studied in connection to brain mechanisms and blood pressure control. Knowing that blood pressure is the regulated variable in this context (Julius, 1988) it is necessary to capture BP, BP variability and the sensitivity of short term blood pressure control (baroreflex sensitivity) in order to get adequate information about cardiovascular state changes. Van Roon et al. (2004) used a simulation model of the baroreflex to show that the effects on task related effort can be explained by a strong decrease of vagal activity in combination with a moderate increase of sympathetic activation. The same model can be applied to study compensatory effort effects or to increase the knowledge about cortical influences on autonomic control. Before this stage is reached, however, more experimental results are necessary on compensatory effort investment. In many studies on natural or simulated working conditions decreases of HR are observed as a function of time, for instance during a working day. In several cases this indicates the presence of fatigue, probably related to diminished invested effort during the day. There is a question mark over whether this is a correct interpretation. In many studies task performance decrements are not found, or only as a shift towards another task strategy at the end of a long working period (making more errors, faster reactions). Mulder et al. (2009) reported a disruption of the initial defense-type response pattern associated with mental effort investment already after only five or ten minutes. According to these authors, this pattern can be characterised by an ongoing increase in blood pressure in combination with: decreased HR, increased baroreflex sensitivity, increased HRV and blood pressure variability (Mulder et al., 2003). According to Van Roons' simulation model, this pattern is explained by a 'recovery' of vagal activation to resting levels while sympathetic activation gradually increases as a function of time.

It is striking that some studies on simulated flight which required higher levels of motor activity relative to cognitive tasks that the baroreflex mediated decrease of HR did not occur as a function of time (Wilson, 1993); in some cases even a distinct increase was observed that may be connected to increased task complexity (De Rivecourt et al., 2008). Therefore, it may be concluded that response patterns of HR and HRV are situation (and task) dependent (Boucsein & Backs, 2000) in applied investigations. Additionally, one must account for the effect of speaking that has a large influence on both HR and HRV, which may fade away any other effects. In this context it is recommended to carefully connect specific demanding task events to short segments of cardiovascular variables and to rule out disturbing artefacts (e.g. speaking) (Mulder et al., 2009).

To conclude: the effects of demanding mental task performance on cardiovascular variables can be described in two basic patterns: (1) a defensive type reaction during short-lasting task performance and during initial phases of long-lasting work, and (2) an increased reaction of the baroreflex as a means for limiting blood pressure increases. During demanding longer lasting tasks, it may be expected that a mix of both patterns will occur continuously.

4. Summary

Mental effort is considered to be a psychophysiological process of energy mobilisation. The goal of this process is to preserve acceptable levels of task performance under conditions of duress, such as increased task difficulty or sleep deprivation. The process is considered to be finite (i.e. may not be sustained indefinitely), associated with a range of costs (e.g. changes in mood) and a manifestation of volitional activity. Research on EEG activity has identified a pattern of frontal theta activation coupled with a suppression of alpha activity. This research has focused primarily on working memory although there is some evidence of this pattern being replicated on other tasks. It is not known whether this measure of computational mental effort will generalise to other stressors (e.g. sleep deprivation, sustained performance) or respond to motivational incentives. There is also a body of experimental evidence supporting the hypothesis that heart rate variability, specifically the 0.1Hz component, is sensitive to cognitive manipulation. It is argued that cardiovascular responses to increased mental effort are assessed within the context of blood pressure control. At the time of writing, there is very little research that seeks to characterise mental effort mobilisation in terms of both EEG activity and the cardiovascular response. It is suggested that mental effort represents a unitary process where autonomic variables respond to the need to transport energy substrates to the brain and cerebral measures capture spatial/temporal correlates of effortful activity in the brain. Further research is required to reconcile both categories of psychophysiological processes as part of the same mechanism.

Acknowledgements

The authors wish to thank Dick de Waard for his stimulating comments on earlier versions of the manuscript.

References

Aasman, J., Mulder, G., Mulder, L.J.M., 1987. Operator effort and the measurement of heart rate variability. *Human Factors* 29 (2), 161–170.

Akselrod, S., Gordon, D., Ubel, F.A., Shannon, D.C., Berger, A.C., & Cohen, R.J. (1981). Power spectrum analysis of heart rate fluctuation: A quantitative probe of beat-to-beat cardiovascular control. *Science*, 213, 220-223.

Althaus, M., Mulder, L.J.M., Mulder, G., van Roon, A.M., & Minderaa, R.B (1998). The Influence of Respiratory activity on the Cardiac Response Pattern to Mental Effort. *Psychophysiology*, 35, 420-430.

Angelone, A., & Coulter, N.A. (1964). Respiratory sinus arrhythmia: a frequency dependent phenomenon. Journal of Applied Physiology, 19, 479-482.

Baars, B. J. (1993). Why volition is a foundation issue for psychology. *Consciousness and Cognition*, 2, 281-309.

Beatty, J. (1986). Computation, control and energetics: a biological perspective. In G. R. J. Hockey, Gaillard, A. W. K. & Coles, M. G. H. (Ed.), *Energetical States Underlying Task Performance* (pp. 43-51). Dordrecht: Martinus Nijhoff.

Berntson, G. G., Cacioppo, J. T., & Grossman, P. (2007). Whither vagal tone. *Biological Psychology*, 74, 295-300

Berntson, G.G., Bigger, J.Th., Eckberg, D.L., Grossman, P., Kaufmann, P.G., Malik, M., Nagaraja, H.N., Porges, S.W., Saul, J.Ph., Stone, P.H., & Van der Molen, M.W. (1997).

Heart rate variability: Origins, methods, and interpretive caveats. *Psychophysiology*, 34 (6), 623-648.

Boucsein, W. & Backs, R. W. (2000). Engineering psychophysiology as a discipline: historical and theoretical aspects. In Boucsein, W. & Backs, R. W. (Eds.) *Engineering Psychophysiology: Issues and Applications* (pp. 3-30). Mahweh, NJ: Erlbaum.

Brehm, J. W., & Self, E. A. (1989). The intensity of motivation. *Annual Review of Psychology*, 40, 109-131.

Cabeza, R., & Nyberg, L. (2000). Imaging cognition II: an empirical review of 275 PET and fMRI studies. *Journal of Cognitive Neuroscience*, 12, 1-47.

Davies, D. R., & Parasuraman, R. (1982). *The Psychology Of Vigilance*. London: Academic Press.

De Rivecourt, M., Kuperus, M.N., Post, W.J., Mulder, L.J.M. (2008). Heart rate and eye movement measures as indices for mental effort during simulated flight. *Ergonomics* 51, 1295–1319.

De Waard, D. (1996). The measurement of drivers' mental workload. PhD thesis, University of Groningen. University of Groningen,

De Waard, D., Kruizinga, A., & Brookhuis, K.A. (2008). The consequences of an increase in heavy goods vehicles for passenger car drivers' mental workload and behaviour: A simulator study. *Accident Analysis and Prevention*, 40, 818-828.

Eysenck, M. W. (1997). *Anxiety and cognition: A unified theory*. Hove, England: Psychology Press.

Fairclough, S. H., & Houston, K. (2004). A metabolic measure of mental effort. *Biological Psychology*, 66, 177-190.

Gendolla, G. H. E. (2000). On the impact of mood on behaviour: an integrative theory and a review. *Review of General Psychology*, 4, 378-408.

Gevins, A., & Smith, M. E. (2003). Neurophysiological measures of cognitive workload during human-computer interaction. *Theoretical Issues in Ergonomic Science*, 4(1-2), 113-121.

Gevins, A., & Smith, M. E. (2006). Electroencephalography (EEG) in Neuroergonomics. In R. Parasuraman & A. A. Rizzo (Eds.), *Neuroergonomics: The Brain at Work* (pp. 15-31). New York: Oxford University Press.

Gevins, A., Smith, M. E., Leong, H., McEvoy, L., Whitfield, S., Du, R., et al. (1998). Monitoring working memory load during computer-based tasks with EEG pattern recognition models. *Human Factors*, 40(1), 79-91.

Gevins, A, Smith, M.E., McEvoy, L. & Yu, D. (1997). High-resolution EEG mapping of cortical activation related to working memory: effects of task difficulty, type of processing and practice. *Cerebral Cortex*, 7, 374-385.

Grossman and Taylor (2007). Toward understanding respiratory sinus arrhythmia: relations to cardiac vagal tone, evolution and biobehavioral functions, *Biological Psychology*, 74, 263–285.

Gundel, A., & Wilson, G. F. (1992). Topographical changes in the ongoing EEG related to the difficulty of mental tasks. *Brain Topography*, 5(1), 17-25.

Guyton, A.C. (1980). *Circulatory physiology III: Arterial pressure and hypertension.* Philadelphia: W.B. Saunders Company

Hancock, P. A., & Desmond, P. A. (2001). *Stress, Workload, and Fatigue*. Mahwah, NJ: Erlbaum.

Hancock, P. A., & Warm, J. S. (1989). A dynamic model of stress and sustained attention. *Human Factors*, 31(5), 519-537.

Helton, W. S., Hollander, T. D., Warm, J. S., Tripp, L. D., Parsons, K., Matthews, G., et al. (2007). The abbreviated vigilance task and cerebral hemodynamics. *Journal of Clinical and Experimental Neuropsychology*, 29(5), 545-552.

Hirsh, J.A., & Bishop, B. (1981). Respiratory sinus arrhythmia in humans: how breathing pattern modulates heart rate. *American Journal of Physiology*, 241, 620-629.

Hockey, G. R. J. (1993). Cognitive-energetical control mechanisms in the management of work demands and psychological health. In A. Baddeley & L. Weiskrantz (Eds.), *Attention: Selection, Awareness and Control*. (pp. 328-345). Oxford: Clarendon Press.

Hockey, G. R. J. (1997). Compensatory control in the regulation of human performance under stress and high workload: a cognitive-energetical framework. *Biological Psychology*, 45, 73-93.

Ishii, R., Kazuhiro, S., Ukai, S., Inouye, T., Ishihara, T., Yoshimine, T., et al. (1999). Medial prefrontal cortex generates frontal midline theta rhythm. *NeuroReport*, 10(4), 675-679.

James, W. (1890). *The Principles of Psychology*. New York: Holt.

Julius, S. (1988). The blood pressure seeking properties of the central nervous system. *Journal of Hypertension*, 6, 177-185.

Kahneman, D. (1973). *Attention and Effort*. Englewood Cliffs N. J.: Prentice-Hall.

Karemaker, J.M. (1987). Neurophysiology of the baroreceptor reflex. In R.I. Kitney and O. Rompelman (Eds.), *The beat-by-beat investigation of cardiovascular function* (pp. 27-49). Oxford: Clarendon Press.

Kennedy, D. O., & Scholey, A. B. (2000). Glucose administration, heart rate and cognitive performance: Effects of increasing mental effort. *Psychopharmacology*, 149, 63-71.

Kramer, A.F. (1991). Physiological metrics of mental workload: A review of recent progress. In D.L. Damos (Ed.), *Multiple-task performance*. (pp. 279-328). London: Taylor & Francis.

Locke, E. A., & Latham, G. P. (1990). *A Theory of Goal Setting and Task Performance.* Englewood Cliffs, NJ: Prentice-Hall.

Mulder, G., & Mulder, L.J.M. (1981). Task-Related Cardiovascular Stress. In J. Long & A. Baddeley (Eds.), *Attention and Performance IX* (pp 591-606). Hillsdale, New Jersey: Lawrence and Erlbaum Associates

Mulder, G. (1986). The concept and measurement of mental effort. In G. R. J. Hockey, A. W. K. Gaillard & M. G. H. Coles (Eds.), *Energetical issues in research on human information processing* (pp. 175-198). Dordrecht, The Netherlands: Martinus Nijhoff.

Mulder, L.J.M, Dijksterhuis, C., Stuiver, A. & de Waard, D. (2009). Cardiovascular state changes during performance of a simulated ambulance dispatchers' task: Potential use for adaptive support. *Applied Ergonomics*, 40, 965-977.

Mulder, L.J.M. (1992). Measurement and analysis methods of heart rate and respiration for use in applied environments. *Biological Psychology*, 34, 205-236.

Mulder, L.J.M., Van Roon, A., Veldman, H., Laumann, K., Burov, A., Quispel, L., Hoogeboom, P.J. (2003). How to use cardiovascular state changes in adaptive automation. In: Hockey, G.R.J., Gaillard, A.W.K., Burov, O. (Eds.), *Operator Functional State. The Assessment and Prediction of Human Performance Degradation in Complex Tasks*. NATO Science Series. IOS Press, Amsterdam, pp. 260–272.

Myles, W.S., Romet, T.T. (1987). Self-paced work in sleep deprived subjects. *Ergonomics* 30, 1175–1184.

Myrtek, M., Deutschmann-Janicke, E., Strohmaier, H., Zimmermann, W.,Lawerenz, S., Brügner, G., Müller, W. (1994). Physical, mental, emotional, and subjective workload components in train drivers. *Ergonomics*, 37, 1195–1203.

Owen, A. M., McMillan, K. M., Laird, A. R., & Bullmore, E. (2005). N-back working memory paradigm: a meta-analysis of normative functional neuroimaging studies. *Human Brain Mapping*, 25, 46-59.

Pagani, M., Rimoldi, O., & Maliani, A. (1992). Lowfrequency components of cardiovascular variabilities as markers of sympathetic modulation. *Trends in Pharmacological Science*, 13, 5054.

Pashler, H. E. (1998). *The Psychology Of Attention*. Mass: MIT Press.

Rompelman, O. (1980). The assessment of fluctuations in heart rate. In: R.I. Kitney& O. Rompelman (Eds.). *The study of heart rate variability*. (pp. 59-77). Oxford: Clarendon Press.

Saravini, F. (1999). Energy and the brain: facts and fantasies. In E. Della Salla (Ed.), *Mind Myths* (pp. 43-58). Chichester, UK: Wiley.

Saul, J.P., Berger, R.D., Chen, M. H., & Cohen, R. (1991). Transfer function analysis of autonomic regulation II. Respiratory sinus arrythmia. *American Journal of Physiology*, 256, 153-161.

Smith, M. E., Gevins, A., Brown, H., Karnik, A., & Du, R. (2001). Monitoring task loading with multivariate EEG measures during complex forms of human-computer interaction. *Human Factors*, 43(3), 366-380.

Smith, M. E., McEvoy, L., & Gevins, A. (1999). Neurophysiological indices of strategy development and skill acquisition. *Cognitive Brain Research*, 7, 389-404.

Stuiver, A. and. Mulder, L.J.M. (2009). On artefact-free real-time computation of cardiovascular measures. In *Proceedings of the IEEE 3rd International Conference on Affective Computing and Intelligent Interaction*, ACII, volume 28

Szirmai, I., Amrein, I., Palvolgyi, L., Debreczeni, R., & Kamondi, A. (2005). Correlation between blood flow velocity in the middle cerebral artery and EEG during cognitive effort. *Cognitive Brain Research*, 24, 33-40.

Van Roon, A.M., Mulder, L.J.M., Althaus, M., Mulder, G. (2004). Introducing a baroreflex model for studying cardiovascular effects of mental workload. *Psychophysiology* 41, 961–981.

Veltman, J. A., & Gaillard, A. W. K. (1998). Indices of mental workload in a complex task environment. *Neuropsychobiology, 28*, 72-75.

Veltman, J.A., Gaillard, A.W.K. (1996). Physiological indices of workload in a simulated flight task. *Biological Psychology*, 42, 323342.

Veltman, J.A., Gaillard, A.W.K., 1998. Physiological workload reactions to increasing levels of task difficulty. *Ergonomics* 41 (5), 656–669.

Warm, J. S., & Parasuraman, R. (2007). Cerebral hemodynamics and vigilance. In R. Parasuraman & M. Rizzo (Eds.), *Neuroergonomics: The brain at work* (pp. 146-158). New York: Oxford University Press.

Wesseling, K.H., & Settels, J.J., (1985). Baromodulation explains shortterm blood pressure variability. In: J.F. Orlebeke, G. Mulder & L.P.J. van Doornen (Eds.), *The psychophysiology of cardiovascular control* (pp. 69-97). New York: Plenum Press.

Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomic Science*, 3, 150-177.

Wilson, G.F. (1993). Air-to-ground training missions: A psychophysiological workload analysis. *Ergonomics*, 36, pp. 1071–1087.

Wilson, G.F. and Fisher, F., 1991. The use of cardiac and eye blink measures to determine flight segments in F-4 crews. *Aviation, Space and Environmental Medicine* 62, pp. 959–961.

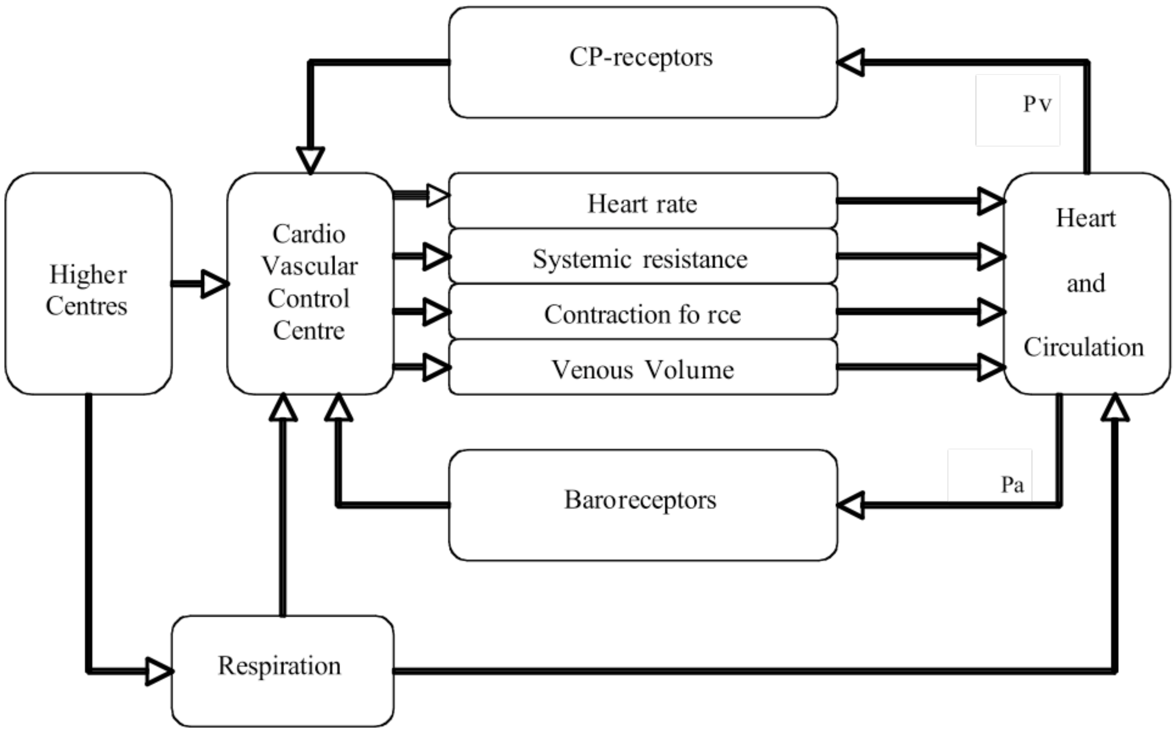
CP-receptors
Pv
Higher Centres
Cardio Vascular Control Centre
Heart rate
Systemic resistance
Contraction fo rce
Venous Volume
Heart and Circulation
Pa
Baroreceptors
Respiration

FIGURE 1