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Biological Psychology 66 (2004) 177–190
BIOLOGICAL PSYCHOLOGY
www.elsevier.com/locate/biopsycho

A metabolic measure of mental effort

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Received 4 January 2003; accepted 9 October 2003

Abstract

Previous studies have operationalised mental effort via various indices of psychophysiology, particularly cardiovascular measures. Metabolic measures represent a complementary approach wherein mental effort investment is explicitly linked to the process of energy mobilisation. The purpose of this study was to contrast cardiovascular variables (heart rate, 0.1 Hz component of heart rate variability) with a metabolic measure (blood glucose) of mental effort. Twenty-nine participants were exposed to Stroop stimuli over a 45 min period under two conditions: (a) congruent (i.e. 100% congruent Stroop stimuli); and (b) incongruent (i.e. 100% incongruent Stroop stimuli). Performance, blood glucose, cardiovascular activity and subjective mood were measured. The results indicated that blood glucose levels were sensitive to both Stroop and time-on-task variables, whilst cardiovascular measures were only sensitive to the latter. There was also evidence of an association between blood glucose levels and response accuracy. The implications of these findings for the operationalisation of mental effort are discussed.

Keywords: Mental effort; Blood glucose; Heart rate variability

1. Introduction

Mental effort investment has been described as energy mobilisation in the service of cognitive goals (Gaillard, 1993, 2001). The mobilisation of mental effort represents a compensatory strategy to protect performance in the presence of increased task demands and psychological stressors (Hockey, 1993, 1997). Mulder (1986) differentiated two categories of mental effort investment; "task effort" being a response to high computational demands

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doi:10.1016/j.biopsycho.2003.10.001

(e.g. novelty, time pressure, multi-tasking, high working memory load, inhibition of an habitual response) and "state effort" required to protect performance from the detrimental influence of fatigue, sleep deprivation, drugs, noise, etc.

Previous research has operationalised mental effort using a variety of psychophysiological variables, including: muscular tension (Wilkinson, 1962), pupil diameter (Beatty, 1982), adrenaline (Frankenhaeuser et al., 1980) and the P300 component (Ullsperger et al., 1988). A substantial number of studies favoured the use of cardiovascular activity to index mental effort. Early studies of heart rate reactivity to psychological tasks (Lacey, 1967) were advanced by data analysis based on fractionalisation, which emphasised a distinction between parasympathetic and sympathetic inputs to cardiovascular control (Obrist, 1981). For example, the T-wave amplitude (TWA) has been associated with both sympathetic control of cardiovascular activity and has been sensitive to temporal demand during an iterative subtraction task (Furedy, 1987; Furedy et al., 1996; Kline et al., 1998). Others employed power spectral analysis to extract parasympathetic influences on cardiovascular control. The mid-frequency component of heart rate variability (0.07–0.14 Hz) (Mulder, 1979, 1985, 1986) is influenced by short-term changes in blood pressure (van der Roon, 1998) and is sensitive to various sources of mental effort such as: increased memory set size and time-sharing in working memory (Aasman et al., 1987; Mulder and Mulder, 1981), complex decision-making (Tattersall and Hockey, 1995) and time pressure (Kamphuis and Frowein, 1985). The 0.1 Hz component has also demonstrated sensitivity to sources of state effort such as: time-on-task (Mascord and Heath, 1992), noise (Mulder et al., 1992), sleep deprivation (Fairclough and Graham, 1999) and the after-effects of work (Meijman, 1995). Despite this substantial body of data, it has also been argued that the sensitivity of the 0.1 Hz component is suspect and tends to distinguish only gross changes in task demands (Jorna, 1992; Nickel and Nachreiner, 2002; Wilson, 1992).

An alternative strategy involves the measurement of metabolic correlates of cognitive activity that represent energy mobilisation at a physiological level. This approach originates from the early days of physiological psychology (Benedict and Benedict, 1933; Goldstein, 1934; Smull et al., 1930). The rationale for the measurement of energy mobilisation is based on two physiological foundations: (a) the brain has substantial energy requirements, i.e. approximately 20–30% of the organism at rest (Benton et al., 1997); and (b) the brain has no storage capacity for energy substrates and the process of aerobic glucose degradation is completely dependent on a constant supply of glucose and oxygen from the bloodstream (Scholey, 2001).

It is common knowledge that hypoglycaemic levels of blood glucose (<2.2 mmol/l) cause a range of physiological and psychological disturbances, e.g. trembling, confusion (Benton et al., 1997). However, recent studies support the view that fluctuations of blood glucose within a normative range may exert a significant influence on cognitive performance. These studies employed a double-blind methodology wherein participants consumed either a glucose drink or a placebo prior to task performance. This approach demonstrated the beneficial influence of elevated blood glucose across a range of cognitive tasks including: working memory (Martin and Benton, 1999), facial recognition (Metzger, 2000), vigilance (Benton, 1990), the Stroop task (Benton et al., 1994), word fluency (Kennedy and Scholey, 2000), multi-tasking (Sunram-Lea et al., 2002), and mental arithmetic (Kennedy and Scholey, 2000; Scholey et al., 2001).

The benefits of increased blood glucose for cognitive performance were particularly apparent when tasks were demanding and effortful. For example, Kennedy and Scholey (2000) reported that elevated glucose only improved performance on a difficult arithmetic task (e.g. serial sevens) but had no effect on an easy version of the same task (e.g. serial threes). Similarly, when performance was sustained over 40 min, the facilitative influence of elevated blood glucose was only apparent during the latter period of the trial when fatigue peaked (Benton et al., 1994). These findings provide a link between the glucose facilitation effect and mental effort investment, i.e. the benefits of elevated blood glucose are most apparent when task- or state-related mental effort investment was necessary to protect performance.

The effect of increased cognitive demands or mental effort investment is an accelerated absorption of glucose from the blood (Donohue and Benton, 1999; Scholey et al., 2001). The physiological capability of the individual to transport glucose across the blood–brain barrier represents an important caveat on this process (Donohue and Benton, 2000). It has been found that individuals with high or stable levels of blood glucose exhibited poorer cognitive performance due to an inability to transport glucose efficiently from the blood to the brain (Donohue and Benton, 1999).

There are two other connections between blood glucose and mental effort, one concerning psychophysiology and another linking effort investment to affective change. Kennedy and Scholey (2000) reported an association between falling blood glucose and accelerated heart rate during the performance of a demanding task. This finding led to a tentative hypothesis that accelerated heart rate under high cognitive demand represented one possible mechanism to expedite the transport of glucose to the brain. It has also been hypothesised that effort investment is associated with psychological costs, such as increased fatigue and tension (Hockey, 1993, 1997). Changes in mood have also been linked to fluctuating levels of blood glucose (Benton, 2002); for instance, Owens et al. (1997) reported an association between falling blood glucose and subjective energy levels whereas an earlier study found evidence of increased tension with a decline of blood glucose (Benton and Owens, 1993). These findings suggest that the affective costs of effort investment postulated by Hockey (1993, 1997) may result from declining blood glucose.

The 0.1 Hz component and blood glucose represent both cognitive and energetical facets of the mental effort concept (Hockey et al., 1986). Aasman et al. (1987) argued that the suppression of the 0.1 Hz component is synonymous with controlled processing (Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977), i.e. cognitive operations which are slow, serial, limited by working memory and subject to task interference. The measurement of blood glucose represents a metabolic approach that describes effortful tasks in more amorphous terms as "fuel-limited" (Scholey et al., 2001). The principle purpose of the current study is to contrast the relative sensitivity and association of the 0.1 Hz component and blood glucose within the same experimental paradigm.

The experiment employed the Stroop task to manipulate task-related mental effort investment. The inclusion of the Stroop manipulation is based on the premise that incongruent Stroop stimuli provoke inhibition of an automatic cognitive activity (word-reading) and the suppression of a strong habitual response represents a source of task effort (Shallice and Burgess, 1993; MacLeod, 1991). The Stroop manipulation was used in the current study to generate dichotomous conditions, a congruent condition that was relatively effortless and an incongruent condition wherein each stimulus demanded effortful inhibition. This stark comparison was selected for two purposes: (a) to function as extreme end-points to assess the sensitivity of psychophysiological variables; and (b) to ensure that an identical level of physical demand was present in both conditions. The participants were exposed to Stroop stimuli over a period of 45 min; the effect of sustained time-on-task was expected to engage state-related effort investment to compensate for the effects of fatigue.

2. Method

2.1. Experimental design

Participants performed a Stroop task for 45 min in two separate sessions: (1) congruent stimuli (i.e. all colour words appeared in a congruent colour); and (2) incongruent stimuli (i.e. all words appeared in an incongruent colour). The experiment used a repeated measures design and the order of condition presentation was counterbalanced across the participant sample.

2.2. Participants

Thirty participants (nine male) volunteered to take part in the study. The study employed a questionnaire to exclude those prospective volunteers who were dyslexic, pregnant, on permanent medication or suffered from diabetes. The participant group had an average age of 24.5 years (age range = 18–56 years). All participants were tested at the same time in the morning. Participants were instructed to abstain from alcohol on the night before the session and to conform to dietary instructions (i.e. to eat a standard breakfast of two pieces of toast with margarine with a glass of water 1 h before the session). One participant failed to comply with dietary instructions during one session and was not used in subsequent data analysis. There was at least 24 h between each experimental session. The University Ethics Committee approved the experimental protocol and written consent was obtained from each participant prior to the first session.

2.3. Experimental task

A computerised version of the Stroop task was developed using Eprime software (PST Ltd.). Four colour words (BLUE, RED, WHITE, GREEN) were presented centrally on a 14 in. colour monitor in letters approximately 3 cm high. A fixation point was presented at the centre of the screen for 2 s before each stimulus. Each stimulus appeared onscreen for 2 s and any response in excess of 2 s was classified as a "miss." The order of stimuli presentation was randomised during each run. Participants responded to each colour word by pressing one of four possible response keys on a standard keyboard. Two keys were colour-labelled (using coloured discs attached to the keys) and operated by the left hand to respond to red and blue stimuli whilst the right hand was used to press colour-labelled keys to respond to green and white stimuli. This labelling was fixed throughout the whole experiment. Both experimental sessions incorporated an initial 2 min period of practice session when participants were exposed to 30 Stroop stimuli followed by three consecutive 15 min trials when participants responded to a total of 675 Stroop stimuli.

2.4. Experimental measures

Performance on the Stroop task was quantified in terms of error frequency (total number of misses and incorrect responses) and mean reaction time for correct responses in milliseconds. Physiological data were collected from two sources. Blood glucose was measured via capillary blood taken from pricked thumbs of both hands. Blood glucose levels were quantified in mmol/l using a HemoCue B-Glucose Analyser in combination with Microcuvettes (HemoCue Ltd.). Blood glucose was collected at four points in time during each session: a pre-test following by three subsequent samples at 15 min intervals following a period of Stroop performance. Three disposable electrodes were attached to the participants' chest to collect electrocardiogram (ECG) data. These data were collected using a PowerLab system in conjunction with Chart software (ADI Ltd.) ECG data were collected continuously throughout the experimental session at a sample rate of 1000 Hz. The ECG data were subsequently analysed to yield average heart rate expressed as mean inter-beat-interval (IBI) and mean power in the 0.1 Hz bandwidth of heart rate variability (HRV) using the heart rate variability extension module provided by the Chart software. Subjective mood data were collected before each session and at 15 min intervals during each experimental run using the UWIST Mood Adjective Checklist (UMACL) (Matthews et al., 1990). The UMACL yields three mood components: energetic arousal (i.e. alert–tired), tense arousal (i.e. tense–relaxed) and hedonic tone (i.e. happy–sad).

2.5. Procedure

Each experimental session was conducted between 9 and 11 a.m. On arrival for their initial session, participants received information on the experimental protocol and provided written consent. Three ECG electrodes were attached to the participant who sat quietly for 10 min whilst baseline data were collected. Blood was taken from the thumb following this period to provide a pre-test level of blood glucose. The participants then received instructions on how to complete the Stroop task and were instructed to respond as quickly and accurately as possible. A 2 min practice session on the Stroop task followed the receipt of instructions. Pre-session mood data were collected at this point and participants completed the first 15 min period of the Stroop task. After 15 min, participants provided a second blood sample and completed a mood questionnaire. The same pattern was followed after participants had completed a second and third 15 min period of task performance. This protocol was repeated during subsequent experimental sessions. The participants were debriefed and received remuneration after the second session.

3. Results

Error rates were calculated based on the total frequency of misses and incorrect responses. These data were analysed via two-way ANOVA (Stroop condition $\times$ time-on-task) using

SPSS v9.0 (SPSS Ltd.). Descriptive statistics for error frequency revealed the presence of one outlier (i.e. a value higher than 2.5 × standard deviation of sample) who was removed from the analysis of performance. The analysis of errors revealed a significant main effect for experimental condition [$F(1, 27) = 9.94$, $P < 0.01$], i.e. post-hoc multiple comparisons with Bonferroni adjustment revealed that errors were more frequent during the incongruent ($M = 15.4$, S.D. = 2.5) condition compared to the congruent condition ($M = 8.7$, S.D. = 0.82). An identical two-way ANOVA was conducted on the mean reaction time data for correct responses. This analysis indicated that responses were faster during the congruent condition ($M = 619.2$ ms, S.D. = 12.5 ms) compared to the incongruent ($M = 662.0$ ms, S.D. = 12.4 ms) condition [$F(1, 27) = 26.6$, $P < 0.01$]. There was no significant effect of time-on-task effect with respect to either the speed or accuracy of responses.

Blood glucose data collected after each 15 min period of performance were subtracted from pre-session levels and subjected to two-way ANOVA analysis (Stroop condition × time-on-task). One participant was identified as an outlier and removed from the analysis. The results of this analysis indicated significant main effects for Stroop condition [$F(1, 27) = 5.56$, $P < 0.05$] and time-on-task [$F(2, 26) = 5.89$, $P < 0.05$]. Post-hoc multiple comparisons with Bonferroni adjustment revealed that blood glucose levels were significantly lower during the incongruent condition compared to the congruent condition, and that blood glucose fell significantly between each successive 15 min period of performance. Mean values for these data are illustrated in Fig. 1.

Heart rate data were quantified as mean inter-beat interval and subtracted from a pre-session baseline value for the purposes of analysis. A two-way ANOVA (Stroop condition × time-on-task) revealed a significant main effect for time-on-task [$F(2, 27) = 12.38$, $P < 0.01$], i.e. the change scores indicated a declining heart rate from the initial period ($M = 40.71$ ms, S.D. = 8.9 ms) to the two subsequent 15 min periods ($M = 68.83$, S.D. = 9.7 and 76.49 ms, S.D. = 8.2 ms, respectively). The IBI data were subjected to a power spectrum analysis to derive mean power in the mid-frequency (0.07–0.14 Hz) bandwidth. The data from the spectral analysis were log-transformed and subtracted from a pre-session baseline value then subjected to the same two-way ANOVA analysis as the IBI data. This ANOVA also revealed a significant main effect for time-on-task [$F(2, 27) = 7.65$, $P < 0.01$]; multiple comparisons with Bonferroni adjustment indicated that the mid-frequency component was significantly suppressed during the initial 15 min of task performance ($M = -0.42$, S.D. = 0.12) compared to the second ($M = -0.22$, S.D. = 0.13) and third ($M = -0.11$, S.D. = 0.12) periods of performance.

Data from the mood adjective checklist were also subtracted from a pre-test baseline in order to study relative changes in mood across each experimental session. The baselined mood data were analysed via two-way ANOVA and descriptive statistics are shown in Table 1. The analysis of energetic arousal revealed higher levels of tiredness during the congruent condition [$F(1, 28) = 6.12$, $P < 0.05$] (Table 1). Two participants were identified as outliers and were excluded from the analysis of tense arousal. This ANOVA revealed an effect of marginal significance for experimental condition [$F(1, 26) = 3.58$, $P = 0.07$], i.e. participants experienced increased tension during the incongruent condition compared to the congruent condition (Table 1). One outlier was identified and excluded from the analysis of hedonic tone. This ANOVA revealed a significant effect for experimental condition [$F(1, 27) = 4.55$, $P < 0.05$] and an interaction effect [$F(2, 26) = 3.79$,

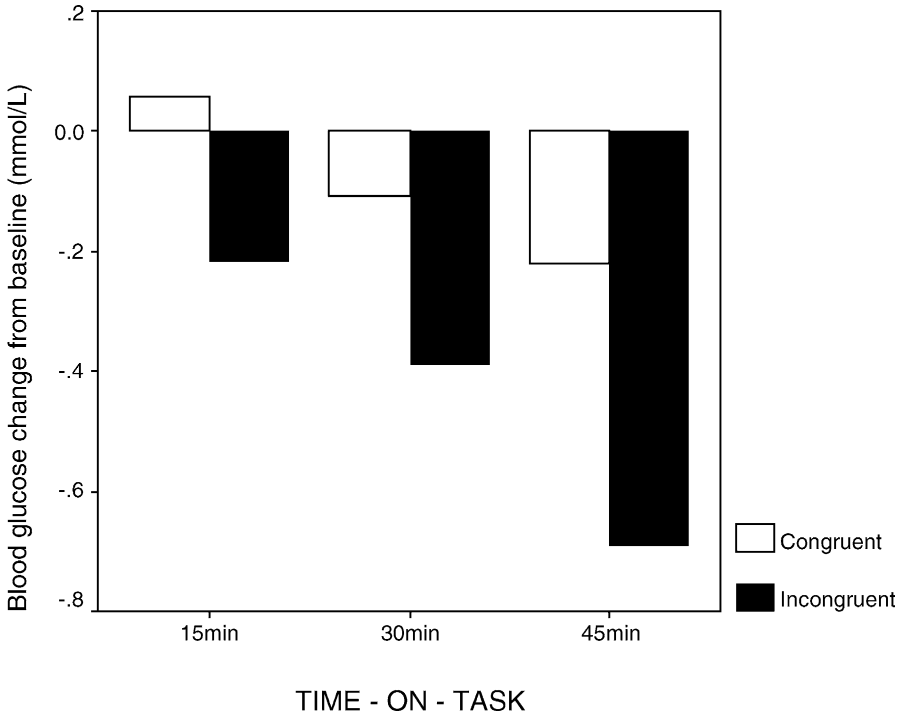

Fig. 1. Mean change in blood glucose levels (mmol/l) from baseline values for both experimental conditions across time-on-task ($N = 28$).

$P < 0.05$]. Participants felt sad during the incongruent condition relative to the congruent condition (Table 1); however, this effect was attenuated by time-on-task and the significant differentiation between both conditions was only apparent after 30 min of performance.

3.1. Correlational analysis

A second analysis was conducted to explore the levels of association between blood glucose, cardiovascular psychophysiology, performance and mood. All values except for performance data were subtracted from a pre-session baseline. This analysis was based

Table 1
Means and standard deviations of energetic arousal ($N = 29$), tense arousal ($N = 27$) and hedonic tone ($N = 28$) for both experimental conditions

Mood component	Congruent condition	Incongruent condition
Energetic arousal	−2.52 [0.41]	−0.45 [0.69]
Tense arousal	−0.31 [0.49]	0.74 [0.41]
Hedonic tone	−1.04 [0.51]	−2.14 [0.42]

Note: These values have been derived by subtracting mood scores from a pre-test baseline score.

Table 2
Correlation coefficients between psychophysiological variables and task error ($N = 27$)

	Task error (15 min)	Task error (30 min)	Task error (45 min)
Blood glucose	0.36	0.32	0.48
0.1 HZ component	0.19	0.21	0.21
Heart rate	0.24	0.24	0.15

Underlined values are significant at the 0.05 level. *Note*: All psychophysiological variables were subtracted from a pre-test baseline prior to analysis.

on the calculation of Pearson's correlation coefficient and was confined to data from the incongruent condition on the basis that patterns of association would be most apparent in the most effortful of the three experimental conditions. The first analysis explored the correlations between psychophysiology and performance. This analysis revealed significant positive correlations between all three psychophysiological variables and task performance. This analysis is shown in Table 2.

The same correlational analysis was performed to investigate the association between blood glucose levels and measures of cardiovascular psychophysiology. There were no significant correlations between blood glucose, the 0.1 Hz component of heart rate variability and heart rate. A third analysis to explore the relationship between blood glucose and three components of subjective mood also failed to reveal any significant coefficients.

4. Discussion

The main finding of the study was to confirm the sensitivity of blood glucose to one specific source of mental effort (i.e. inhibition of an automatic response) in the absence of a glucose drink. This result confirmed earlier findings (Benton et al., 1994; Kennedy and Scholey, 2000; Scholey et al., 2001). It was also apparent that blood glucose was sensitive to the influence of time-on-task (Fig. 1). Both independent variables caused levels of glucose in the blood to decline as a result of increased energy mobilisation.

The 0.1 Hz component of heart rate variability was only significantly influenced by time-on-task. The insensitivity of the 0.1 Hz component to a manipulation of difficulty within the same task confirmed earlier findings, e.g. Veltman and Gaillard (1996). Several factors are known to confound the sensitivity of the 0.1 Hz component (Boucsein and Backs, 2000; Jorna, 1992) but these elements were either controlled (e.g. physical demands) or absent (e.g. irregular breathing rate due to speech) within the current study. It was also possible that the sensitivity of the 0.1 Hz component was confounded by a reduction of respiratory rate instigated by increased parasympathetic inhibition as a response to either low task demands or increased time-on-task (Wientjes, 1992); there is evidence this type of low-frequency respiratory activity ($<$0.15 Hz) may confound the 0.1 Hz component (Veltman and Gaillard, 1998).

The analysis of performance produced the expected finding that higher error rates and reaction times were associated with incongruent Stroop stimuli. The time-on-task manipulation failed to exert a significant influence on performance; therefore, there was no evidence of fatigue or any learning effect with respect to the either the speed or accuracy of responses. The low-demand congruent task condition induced the expected changes in mood, provoking increased tiredness in participants. Similarly, the demanding incongruent condition was associated with aversive costs (Hockey, 1997) associated with effort investment such as increased tension and negative affect (Table 1).

The analysis shown in Table 2 provided a simple index of the predictive validity of both metabolic and cardiovascular measures in relation to performance quality. These coefficients were modest and despite evidence of statistical significance for blood glucose, there was little to distinguish the three psychophysiological variables. This convergence suggested that a reduction of blood glucose, suppressed power in the mid-frequency bandwidth and increased heart rate were associated with fewer errors.

There was no evidence to support the hypothesis proposed by Kennedy and Scholey (2000) that falling blood glucose was associated with increased heart rate. The influence of time-on-task exhibited the opposite trend as both blood glucose and heart rate declined with increased time-on-task whilst the correlation coefficient between both variables was insignificant. Kennedy and Scholey (2000) used shorter duration tasks (e.g. <3 min) than the current study and their findings may reflect a phasic pattern of heart rate reactivity that was not sustained over an extended period. The study also failed to replicate previous findings (Benton and Owens, 1993) linking declining blood glucose levels to changes in mood.

The correlational analysis (Table 1) indicated that both blood glucose and the 0.1 Hz component had a similar association with task performance. However, the influence of time-on-task on both measures was contradictory. The reduction of blood glucose with time-on-task indicated a sustained mobilisation of energy whereas increased power of the 0.1 Hz component represented a reduction of mental effort over the course of the task. It is not unknown for two psychophysiological indicators to exhibit trends in opposite direction and still represent a single underlying process (Lacey, 1967). It may be that the 0.1 Hz component is particularly sensitive to increased parasympathetic inhibition (Backs and Selijos, 1994) induced by a sustained, monotonous task. It is possible that the 0.1 Hz component is more sensitive to task-related sources of effort (e.g. variables associated with computational demand) as opposed to state effort (Mulder, 1986). The reasons for this inconsistency are difficult to evaluate given the ambiguous relationship between mental effort and time-on-task effects. The influence of sustained time-on-task may prompt effort investment to protect performance from the influence of fatigue, boredom etc. This hypothesis is supported by the blood glucose data shown in Fig. 1. It is equally plausible for mental effort to decline over time due to influence of f atigue/boredom/disengagement or even a learning effect that improves the efficiency of performance (Eysenck and Calvo, 1992). This interpretation is supported by the 0.1 Hz component data. The absence of any significant time-on-task effect with respect to performance makes it difficult to substantiate either account.

This problem of interpretation stems from the identification of multiple and diverse psychophysiological variables with a broad cognitive-energetical concept of mental effort. If mental effort is defined as energy mobilisation in an inclusive sense then it is possible to operationalise mental effort as any measure of sympathetic activation in the CNS. The problems of this inclusive approach for theory building are similar to those that undermined the concept of unidimensional arousal (Hancock, 1988; Hockey, 1986). A restricted operationalisation of energy mobilisation would link catabolic processes and their physiological substrates to performance efficacy without evoking the CNS as a whole. This operationalisation of mental effort would include blood glucose levels alongside other catabolic variables such as: oxygen consumption/carbon dioxide output (Backs and Selijos, 1994; Carroll et al., 1986), respiratory rate/breadth/depth (Wientjes, 1992), cerebral blood flow (Hitchcock et al., 2003) and measures of neuroendocrinology (Frankenhaeuser, 1987; Peters et al., 1998). This identification of mental effort as energy mobilisation in a literal sense is susceptible to the criticism of oversimplification (Posner and Rothbart, 1986), however it has the advantage of operationalising a fuzzy cognitive-energetical concept with a greater degree of precision.

The current findings support the use of blood glucose as an index of mental effort on the grounds of sensitivity (Fig. 1), consistency (i.e. blood glucose fell in response to both main effects as shown in Fig. 1) and face validity (i.e. if mental effort is conceptualised as energy mobilisation, then metabolic measures are the obvious candidates to index this process). However, this study was limited in several important respects. The comparison between blood glucose and cardiovascular indices of mental effort was inadequate in the sense that certain variables were not included, e.g. TWA (Furedy, 1987), and the study employed a unidimensional indicator of baroreflex sensitivity that has been abandoned by some researchers in favour of complex, multidimensional measures, e.g. the temporal relationship between blood pressure and the 0.1 Hz component of heart rate variability (Mulder et al., 2002; Veltman and Gaillard, 1996). Subsequent research would benefit by extending the array of cardiovascular measurement in terms of both the frequency and complexity of variables.

The most serious limitation of the current study was the Stroop manipulation used to manipulate the level of mental effort investment. It was clear from the performance data that the incongruent condition produced slower responses with a higher error rate. However, the absence of any time-on-task effect indicated that either the incongruent manipulation was insufficiently demanding to induce a performance decrement due to fatigue, or that the repetitive nature of the task introduced a practice effect which effectively cancelled out the influence of fatigue. The specific problems of the Stroop manipulation are overshadowed by the more elementary predicament of selecting a mental effort manipulation per se. Mental effort has been identified with controlled processing, e.g. (Hockey, 1997; Mulder, 1986), but the effort concept has been studied using a wide range of independent variables: e.g. time pressure during iterative subtraction (Furedy, 1987), memory set size for letters (Aasman et al., 1987), complexity of mental arithmetic task (Ullsperger et al., 1988), mental arithmetic versus simple key pressing task (Peters et al., 1998), tracking difficulty in a flight simulator (Veltman and Gaillard, 1996). This diversity makes it difficult to either justify or reject the suitability of the Stroop manipulation used in the current study. It is also problematic to generalise from the current experiment with any degree of confidence. Therefore, the study is presented as one step of a research programme to substantiate the measurement of naturalistic fluctuations of blood glucose in order to index mental effort. The importance of replication of the current findings across a broad range of independent variables, e.g. working memory load, time pressure, and novel decision-making, cannot be underestimated. The same logic applies to the use of time-on-task as a manipulation of state effort. It would be ideal for future work to extend this manipulation by incorporating other sources of state effort, e.g. sleep deprivation, noise, financial incentives etc.

5. Conclusions

A measure of mental effort should be sensitive to both the computational demands and the presence of biological/environmental stressors. Blood glucose fulfilled these criteria within the limited context of the current study whereas the 0.1 Hz component of heart rate variability did not. In addition, both main effects represented the expected decline of blood glucose indicative of increased mental effort and energy mobilisation in response to task- and state-related variables.

The identification of mental effort investment with the mobilisation of physiological energy favours an energetical conceptualisation as opposed to the cognitive interpretation favoured by the 0.1 Hz component. The current study found no evidence of any coherent association between cardiovascular and metabolic measures of mental effort. However, the current study was limited and further research is required to substantiate this finding and to address a fundamental question: can a cognitive-energetical concept of mental effort be operationalised in a consistent fashion or should the construct be deconstructed into cognitive and energetical facets? Substantial evidence already exists to support the view that blood glucose is sensitive to cognitive variables and the current study supports the hypothesis that energetical variables (e.g. time-on-task) exerted an influence on blood glucose. It is hoped that the utility of catabolic measures of mental effort will be investigated in greater detail by future studies.

Acknowledgements

The authors wish to acknowledge assistance and advice from Prof. Donald MacLaren and Mr. Dave Stokes from the School of Sports Science at Liverpool John Moores University. We would also like to thank two anonymous referees for their constructive comments on an earlier version of this manuscript.

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