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The influence of task demand and learning on the psychophysiological response

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Abstract

The level of expertise of an operator may significantly influence his/her psychophysiological response to high task demand. A naïve individual may invest considerable mental effort during performance of a difficult task and psychophysiological reactivity will be high compared to the psychophysiological response of a highly skilled operator. A study on multitasking performance was conducted to investigate the interaction between learning and task demand on psychophysiological reactivity. Thirty naïve participants performed high and low demand versions of the Multi-attribute Task Battery (MATB) over a learning period of 64 min. High and low task demand setting were preset via a pilot study. Psychophysiological variables were collected from four channels of EEG (Cz, P3, P4, Pz), ECG, EOG and respiration rate to measure the impact of task demand and learning. Several variables were sensitive to the task demand manipulation but not time-on-task, e.g., heart rate, Θ activity at parietal sites. The sensitivity of certain variables to high demand was compromised by skill acquisition, e.g., respiration rate, suppression of α activity. A sustained learning effect was observed during the high demand condition only; multiple regression analyses revealed that specific psychophysiological variables predicted learning at different stages on the learning curve. The implications for the sensitivity of psychophysiological variables are discussed.

Keywords: EEG; ECG; EOG; Mental workload; Skill aquisition

1. Introduction

In the mental workload literature, psychophysiological measurement is frequently used to index the level of cognitive demand associated with a task (Boucsein and Backs, 2000; Hancock and Desmond, 2001). The sensitivity of psychophysiology to cognitive demand (e.g., increased temporal demands, multiple task performance etc.) is characterised by neurophysiological changes as well as a shift to catabolic activity within the autonomic nervous system (ANS). These changes have been associated with energy mobilisation and the investment of mental effort (Fairclough and Houston, 2004; Gaillard, 2001).

There is ample evidence that psychophysiological variables respond in a predictable fashion to cognitive

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demand. For instance, increased task difficulty (e.g., increased working memory load) is associated with a characteristic pattern of electroencephalographic (EEG) activity: increased power in the β bandwidth, increased activity in Θ activity at frontal sites and suppression of α activity (Gevins and Smith, 2003; Klimesch, 1999; Wilson et al., 1999; Gevins et al., 1998; Yamada, 1998). A number of cardiovascular measures derived from the electrocardiogram (ECG) have been used to successfully index fluctuations in task demand (Berntson et al., 1997; Mulder et al., 1992; Roscoe, 1992; Veltman and Gaillard, 1996; Wilson and Fisher, 1991). These studies demonstrated that heart rate tends to increase when demand is high. The spectral analysis of heart rate variability (HRV) reveals a suppression of the 0.1 Hz mid-frequency component (sinus arrhythmia) under conditions of increased cognitive demand, e.g., problem solving, increased working memory load (Aasman et al., 1987; Mulder, 1986; Mulder et al., 2002; Tattersall and Hockey, 1995; Veltman and Gaillard, 1996, 1998; Wilson and Fisher, 1991). The high-frequency component of HRV known as vagal tone or respiratory sinus arrhythmia (RSA) functions as an indicator of parasympathetic activity (Porges, 1995) and tends to decrease when task demand is high (Backs et al., 1991; Mulder et al., 2002). The vagal tone measure is influenced by the rate of respiration, which tends to increase under high working memory load or when a person is multitasking (Backs et al., 1991; Backs and Selijos, 1994; Wientjes, 1992). Measures of eye blink duration and frequency derived from the electrooculogram (EOG) are sensitive to cognitive demand if interaction with the task is primarily visual. Both eye blink duration and blink rate decrease with increased demand, presumably to maximize the availability of visual information (Brooking et al., 1996; Goldstein et al., 1992; Veltman and Gaillard, 1996, 1998; Wilson and Fisher, 1991).

This widespread pattern of electrocortical activation, increased respiration and heart rate is broadly representative of energy mobilisation or mental effort to meet increased task demand. At a cognitive level of analysis, mental effort was characterised by Hockey (1993, 1997) as controlled processing, i.e., a slow, serial mode of information processing limited by working memory capacity (Fisk et al., 1987; Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977). The investment of mental effort is synonymous with a switch into a controlled mode of information processing in response to increased complexity, temporal demands and other determinants of high cognitive demand. According to Hockey (1993, 1997), increased mental effort may be accompanied by a number of tactical changes to improve the efficiency of performance, particularly for complex, multifaceted tasks. For example, a participant may choose to attend to an area of the visual array where targets are highly probable while neglecting those areas where targets appear infrequently; similarly, a participant may decide to strategically neglect low-priority or undemanding subtasks in order to sustain performance on critical/demanding task components. The investment of mental effort is characterised as a coordinated, cognitive-energetical response, encompassing catabolic changes at a physiological level and strategic adjustments at a cognitive level (Hockey, 1993, 1997).

The acquisition of skill represents one means of uncoupling the linear relationship between cognitive demand and mental effort investment. Initial stages of learning are characterised by high mental effort and the production of slow, deliberate and often inaccurate responses (Newell, 1988; Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977; Underwood, 1982; Welford, 1976). Repeated practice leads to a formulation of strategy wherein those cognitive processes responsible for effective performance are reinforced and automated (Anderson, 1993; Logan, 1985; Schneider, 1985). This process permits the individual to rationalise and reduce mental effort investment; that is, a pattern of sustained effort investment characteristic of the novice develops into an expert strategy of transient, selective effort investment. This reduction of mental effort effectively reduces the level of mental workload experienced by the individual (Bainbridge, 1978; Hockey, 1996; Welford, 1978). The transition from novice to an expert also has implications for the efficiency of performance (Eysenck and Calvo, 1992; Schonpflug, 1986); a skilled person may produce adequate performance on a demanding task with minimal investment of mental effort whereas a novice could not.

A reduction of mental effort during skilled performance may be characterised within the cognitive domain by an increase of automatic information processing at the expense of effortful, controlled processing (Schneider and Fisk, 1982). This shift is associated with a number of physiological consequences as the requirement to invest mental effort is alleviated. It is presumed that catabolic activity in the ANS is reduced as skill develops, reflecting a decline of sympathetic activation or rising parasympathetic inhibition, which may be achieved via various modes of ANS control, e.g., coupled, uncoupled, coactivation (Berntson et al., 1991, 1994). Neuroimaging studies have revealed specific changes in brain activation during learning that parallel the decline of catabolic activity in the ANS (Haier et al., 1992); the process of skill acquisition leads to a declining activation in those regions of the neocortex not required for task performance. These changes provide evidence of improved neurophysiological "efficiency," as performance necessitates lower levels of brain activation during the transition from novice to expert (Parks et al., 1989). The development of cognitive skill also yields characteristic changes in EEG activity (Smith et al., 1999). This study captured EEG activity as participants developed expertise with verbal/spatial versions of a working memory task as well as a visuomotor video game. Their results indicated an increase of centrally distributed α activity with practice that was indicative of reduced cortical activation (Larson et al., 1998). In addition, frontal midline Θ activity increased as participants learned the tasks; an increase of frontal Θ has been associated with states of focused concentration that may be necessary to maintain an appropriate mental set for task performance (Gevins and Smith, 2003; Gevins et al., 1998).

The antagonism between expertise and cognitive demand produces a dynamic between the investment and conservation of mental effort, which has consequences for the sensitivity and diagnosticity of psychophysiological variables as measures of task demand or mental workload (O'Donnell and Eggemeier, 1986; Wierwille and Eggemeier, 1993). A sensitive variable responds to those independent variables associated with demand (e.g., complexity, multitasking) and is capable of differentiating between different levels of the independent variable (Backs and Selijos, 1994; Fournier et al., 1999; Veltman and Gaillard, 1998; Verwey and Veltman, 1996). The sensitivity of psychophysiological variables to task demand is determined, to an extent, by the expertise of the individual. In the case of skilled performance, psychophysiological measurement may be unresponsive to high cognitive demands because the level of mental effort required is minimised by expertise. Alternatively, the sensitivity of psychophysiological variables to cognitive demand may be a transient effect that represents the temporary naivety of an unskilled individual. When a variable is highly diagnostic, it responds in a manner unique to an independent variable and remains uncontaminated by confounding variables such as physical activity, room temperature etc. There is an open question as to whether psychophysiological variables are sufficiently diagnostic to index cognitive demand while remaining impervious to the influence of expertise.

The interaction between the psychophysiological response and cognitive demand is further clouded by the relationship between task difficulty and the potential for learning. When skill reaches a maximum level, i.e., when cognitive efficiency has peaked and physical limitations constrain any further improvement of performance, the individual has reached the data-limits of task efficiency (Kramer and Spinks, 1991; Norman and Bobrow, 1975) where any further investment of mental effort cannot increase performance quality. Data-limits may be reached within 1 or 2 min of practice for simple, repetitive tasks and the performance differential between expert and novice may be insignificant. By contrast, the potential for learning and performance augmentation increases dramatically for demanding, complex and multifaceted tasks. For example, a multitasking environment such as the Multi-attribute Test Battery (MATB; Comstock and Arnegard, 1992) requires mastery of up to four subtasks as well as the development of timesharing skills (Ackerman et al., 1984; Damos and Wickens, 1980; Lintern and Wickens, 1991). Therefore, sustained practice is required to reach the data-limits on complex compared to simple tasks but the relative improvement of performance is considerable.

A study was performed to investigate how the sensitivity and diagnosticity of psychophysiological variables to task demand was influenced by skill acquisition. Participants were exposed to high and low levels of task demand over a sustained period of learning, e.g., 64 min. A demanding and multifaceted task (MATB) was used to maximise the potential for learning and performance augmentation.

2. Method

2.1. Participants

Thirty university students participated in the experiment (12 female and 18 male). All received a financial reward for their time. The age of participants ranged from 18–40 years (M=21.9 years, S.D.=4.16). Potential participants were excluded if they were pregnant, on medication or reported any known cardiovascular problems. Participants were requested not to consume alcohol on the night before the test session and to abstain from caffeine and strenuous exercise on the morning of the session.

2.2. Experimental task

The Multi-attribute Task Battery (MATB: Comstock and Arnegard, 1992) was used as the experimental task for this study. Three components of the MATB were employed: tracking, system monitoring and resource management tasks. All were pre-scripted to either a high or a low level of task demand.

The parameters for high and low task difficulty were established by a prior pilot study involving 11 participants (none of whom took part in the main study). The pilot participants performed four versions of the MATB for a period of 5 min; each version differed in terms of the difficulty associated with each MATB subtask. On completion of each version, they completed the NASA Task Load Index (TLX) (Hart and Staveland, 1988) without the paired comparison procedure, i.e., the raw Task Load Index (RTLX; Byers et al., 1989). A MANOVA on the RTLX subscales revealed that the most demanding version of the MATB induced a significantly higher level of subjective mental workload (M=65.6) compared to the version producing the lowest level of task demand (M=48.6) [$F(3,5)=7.33$, $p<0.01$]. These two versions of the MATB were used to provide operationalisations of high and low task demand.

A three-task version of the MATB was used for this study. The compensatory tracking task was controlled via a joystick and tracking performance was calculated as root-mean-square (RMS) error from the central point. This task required participants to maintain a moving circle (1 cm in diameter) centred on a 0.5 cm by 0.5 cm central cross by using a joystick. The tracking task used a 4:3 horizontal-to-vertical sine wave driving function and difficulty levels were set using default settings described in Comstock and Arnegard (1992). RMS was calculated by measuring the distance from the central point as horizontal and vertical pixels, which was expressed as sum of squares (SS); therefore, RMS=SQRT (SS/N) where N is the number of data points. The monitoring task comprised a set of four gauges with moving pointers. Under normal conditions, the moving pointers fluctuated around the centre point of each gauge. Participants were instructed to inspect the gauges for pointer deflections that were more than one notch above or below the centre point, and to make the appropriate keyboard response (via one of four keys) as soon as one was detected. Pointer deflections not detected within 15 s were automatically corrected and scored as missed signals and responses to nonsignals were scored as false alarms. For high task demand, the event rate was 30 deflections per min, and for low demand, there were 2 deflections per min. The resource management task required participants to maintain a specific level of fuel (i.e., 2500 units) within both of the main tanks (A and B), which are constantly depleting. This task is complicated by the occurrence of ‘pump failures’ (faults), whereby the pumps are out of use for a set period and fuel cannot be transferred using those particular pumps. For high demand, 1–2 pumps were scripted to fail for approximately 15 s every min, and for low demand, 1 pump was failed for 5 s every min. Performance on the resource management task was measured by calculating the deviation from the required level of (2500) units in tanks A and B.

2.3. Psychophysiological measures

EEG was recorded using silver chloride (Ag/AgCl) coated electrodes and sampled at 500 Hz. The measures of electrocortical activity were taken from four sites found to be most effective indicators of task engagement during MATB performance (Pope et al., 1995): Cz, Pz, P3 and P4 (Jasper, 1958). A ground site was located midway between Cz and Pz. Each site was referenced to the left and right mastoid areas. Four BIOPAC EEG100C differential (high gain), bioelectric potential amplifiers were used to record EEG (one amplifier module for each EEG site). The high and low band pass filters were set at 0.1 Hz and 35 Hz, respectively. The EEG signals were analysed via Fast Fourier Transform (FFT) in steps of 2.65 s with an overlap of 0.5 s. The absolute mean power was extracted from three EEG bandwidths: theta (Θ) (4.3–7.8 Hz), alpha (α) (8.2–12.9 Hz), and beta (β) (13.3–21.9 Hz), for each of the four sites. In addition, the total power from 4.3–21.9 Hz was calculated as head movement and other physical artifacts tend to inflate power in the FFT analysis. A macro was derived to check the total power of each EEG epoch and reject those epochs whose total power exceeded 200% of the average value for that data record (the 200% figure was derived based on visual detection of artifacts in the EEG record). This procedure led to an average rejection rate of 1.4% for all epochs per data record.

To assess vertical eye blink activity, Ag/AgCl electrodes were placed above and below the left eye, with a ground electrode positioned in the centre of the forehead. The EOG signals were filtered at 0.05–35 Hz, and amplified by a BIOPAC EOG100C differential (high gain), corneal–retinal potential amplifier. This signal was smoothed and subjected to a threshold analysis to yield positive spikes which identified the onset and offset of each eye blink; blink rate and duration were derived from this transformed signal.

To measure heart activity, vinyl electrodes were positioned on the seventh intercostal space on the right and left side of the body. A common ground electrode was placed on the hip on the right side of the body. ECG was measured using a BIOPAC TEL 100C differential (high gain) amplifier. The high and low band pass filters were set at 0.5–35 Hz, respectively. R peaks of the ECG were detected offline, and the interbeat interval (IBI) between successive R waves was calculated. These data were subjected to computerised analysis via the CARSPAN software programme (L.J.M. Mulder et al., 1995). This software analysis proceeds in two phases: the data are initially evaluated for missed and ectopic beats (average percent per participant data record was 2.82). The former were corrected via interpolation and the latter were discarded) then a FFT analysis is performed to quantify HRV in mid (0.09–0.13 Hz)- and high (0.14–0.40 Hz)-frequency bands.

Respiration was monitored using an elastic belt placed around the chest to measure expansion during breathing. Respiration signals were again amplified using a (differential, high gain) BIOPAC TEL100C remote monitoring module, with the filter settings at 0.05–35 Hz. Peaks from the signal were detected with BIOPAC AcqKnowledge software, and used for the calculation of respiration rate (i.e., breaths per min). The sample rate for ECG, EOG and respiration was 500 Hz.

2.4. Procedure

Upon entering the laboratory, participants were briefed about the nature of the experiment. Those who chose to participate were already fully informed as to the procedures involved in the recording of the physiological measures. Participants were prepared so their physiology could be recorded (e.g., the location of the electrode sites, the mild abrasion of skin, the attachment of the electrodes etc.), and this was followed by a 15-min baseline period for all of the physiological variables. During this baseline period, the participants were asked to lie back and relax (with their eyes open) while their physiology was measured.

Participants were instructed about the objectives of each experimental task and then presented with a 5-min familiarisation session, which incorporated both high and low levels of task demand. After the familiarisation session, participants performed the formal task session of 4×16 min blocks of MATB performance (64 min in total). All 16-min blocks contained two 4-min periods of both high and low task difficulty, which were presented as one of four possible combinations: (i) Low, High, Low, High; (ii) High, Low, High, Low; (iii) Low, High, High, Low; (iv) High, Low, Low, High. The order of presentation for these four blocks was counterbalanced across participants.

3. Results

Experimental data were analysed via multivariate analyses of variance (MANOVA) using SPSSv.11. Outliers, defined as values lying at least three standard deviations outside the group mean, were excluded from all analyses.

3.1. MATB performance

Performance on the tracking task was represented by the RMS error and these data were subjected to a 2×4 ANOVA. Two participants were omitted as outliers. This analysis revealed two main effects for task demand [$F(1,28)=208.7$, $p<0.01$, $\eta=0.885$] and time-on-task [$F(3,25)=19.38$, $p<0.01$, $\eta=0.699$]. Tracking error increased during periods of high task demand ($M=54.9$) compared to low demand ($M=28.5$). In addition, tracking error increased in a linear fashion from the initial ($M=33.5$) to the final period of performance ($M=47$).

The efficacy of performance on the resource management task was scored as the mean deviation from the target value of 2500 units, i.e., higher deviation=poorer performance. A 2×4 ANOVA revealed a main effect for task demand [$F(1,30)=57.84$, $p<0.01$, $\eta=0.658$] and time-on-task [$F(3,28)=3.47$, $p<0.05$, $\eta=0.271$]. Post-hoc tests revealed poorer performance during high demand ($M=429.97$) compared to low demand ($M=292.38$) and a significant decline of the deviation score between the initial period and all subsequent periods of performance. This ANOVA also yielded a significant interaction effect [$F(3,28)=3.44$, $p<0.05$, $\eta=0.269$] and this effect is illustrated in Fig. 1. Post-hoc tests revealed a consistent and significant decline of deviation over time-on-task during the high demand condition; however, during the low demand condition, the decline of deviation was only significant from period 1 to period 2 ($p<0.05$; Fig. 1).

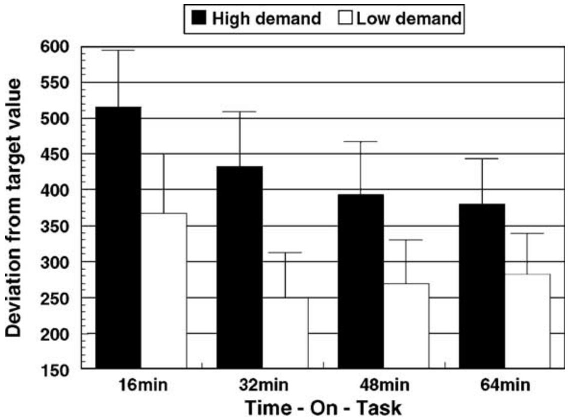

Fig. 1. Performance on the resource monitoring subtask of the MAT Battery over task demand and time-on-task. Performance is expressed as the mean deviation from the target level of fuel to be sustained ($N=30$).

Performance on the gauge monitoring task was measured by three dependent variables: (1) number of missed deflections (misses), (2) number of responses made in the absence of any gauge deflection (false alarms), and (3) mean reaction time to detected gauge deflections. Three participants were removed from this analysis as outliers. These variables were subjected to MANOVA analyses and post-hoc testing for significant effects. The MANOVA revealed significant interactions between dependent variable×task demand [$\Lambda(2,25)=12.38$, $p<0.01$, $\eta=0.498$] and dependent variables×time-on-task [$\Lambda(6,21)=6.08$, $p<0.01$, $\eta=0.635$]. The results of the post-hoc analyses with descriptive statistics are presented in Table 1. The effect of high task demand was to reduce the number of misses and false alarms. As participants gained more experience with the task, the number of misses and the mean reaction time fell; however, the number of false alarms tended to increase with time-on-task (Table 1).

3.2. EEG data

EEG data were subjected to a 4-factor MANOVA analysis (site×task demand×time-on-task×EEG band). This analysis revealed a significant interaction between time-on-task and EEG band [$\Lambda(8,21)=9.07$, $p<0.01$, $\eta=0.781$]. Post-hoc testing revealed that mean power in Θ and β bands was higher during task activity compared to baseline levels and this increase was sustained across time-on-task ($p<0.05$). By contrast, levels of α activity were suppressed during task performance (relative to baseline) during the initial 32 min of performance but this effect dissipated during the second half of the task period. These effects are illustrated in Fig. 2.

The EEG MANOVA also revealed a significant interaction between EEG site×task demand×EEG bandwidth [$\Lambda(6,23)=4.65$, $p<0.01$, $\eta=0.548$]. Post-hoc testing revealed that Θ activity increased during periods of high demand compared to low demand at sites P3 ($M=0.95$ vs. 0.90) and Pz ($M=0.91$ vs. 0.94).

Table 1
Results of analyses and descriptive statistics for the gauge monitoring subtask

	Task demand					Time-on-task						
	F	p	*η*	High	Low	*F*	*q*	*η*	16 m	32 m	48 m	64 m
Misses (%)	4.16	0.05	0.14	4.59	6.13	3.49	<0.05	0.34	8.87	6.79	4.27	3.61
FA (%)	26.31	<0.01	0.50	19.9	34.6	8.36	<0.01	0.51	21.5	25.7	28.9	32.9
RT (ms)		N S		5.2	5.2	6.05	<0.01	0.43	5.74	5.41	5.14	4.63

Misses refers to the percentage of gauge deflections where no response was made, FA refers to the percentage of false alarms (responses made when no gauge deflection had occurred) and RT represents the mean reaction time (N=27).

3.3. ECG and respiration

The ECG signal was analysed in terms of three variables: (a) inter-beat interval (IBI), (b) power in the mid-frequency 0.09–0.13 Hz bandwidth (the 0.1-Hz component), and (c) power in the high-frequency 0.14–0.40 Hz bandwidth (vagal tone). Respiration rate was quantified as the number of breaths per minute. All four variables were analysed via MANOVA which revealed a significant interaction between task demand×time-on-task×dependent variable [$\Lambda(12,11)=4.06$, $p=0.01$ $\eta=0.816$].

A univariate analysis of IBI revealed significant main effects for both time-on-task [$F(4,26)=10.51$, $p<0.01$, $\eta=0.618$] and task demand [$F(1,29)=30.93$, $p<0.01$, $\eta=0.516$]. The first finding revealed that IBI was lower during all periods of task activity relative to the baseline period. The second significant finding indicated that IBI was reduced during episodes of high demand (M=880 ms) compared to low demand (M=897 ms).

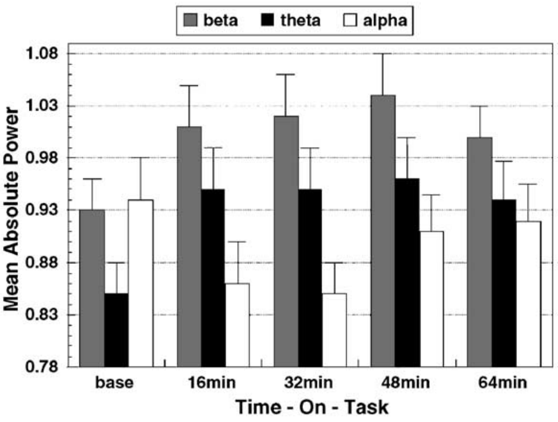

Fig. 2. Mean absolute power in the EEG bandwidths ($\Theta\ \alpha\ \beta$) across time-on-task (N=30).

Both measures of 0.1-Hz component and vagal tone were based on power spectrum analysis using the CARSPAN software package. The resulting power values from both analyses were subjected to a natural log transformation prior to ANOVA. Unfortunately, artifacts in the ECG data record prevented accurate analysis of data from five participants for these variables. The analysis of vagal tone revealed a significant main effect for time-on-task [$F(4,21)=5.51$, $p<0.05$, $\eta=0.187$] and task demand [$F(1,24)=12.68$, $p<0.01$, $\eta=0.345$]. Inspection of mean values revealed that vagal tone declined from baseline (M=7.93) during task activity and was significantly suppressed during high demand (M=7.42) compared to low demand (M=7.54).

The analysis of the 0.1-Hz component revealed a significant main effect for time-on-task [$F(4,26)=12.15$, $p<0.01$, $\eta=0.624$], i.e., power values for 0.1 Hz showed a significant increase with task duration. This ANOVA also revealed a significant interaction effect [$F(4,21)=4.51$, $p=0.01$, $\eta=0.381$], which is illustrated in Fig. 3. Post-hoc tests revealed a significant suppression of the 0.1-Hz component from baseline during the high demand condition; in addition, the 0.1-Hz component was significantly suppressed during the first period for high demand compared to the low demand. However, this trend was reversed during the final period of performance when the 0.1-Hz component was significant suppressed during low demand ($p<0.05$).

The analysis of respiration rate revealed significant main effects for both task demand [$F(1,27)=7.68$, $p=0.01$, $\eta=0.222$] and time-on-task [$F(3,25)=8.96$, $p<0.01$, $\eta=0.552$]. There was also a significant interaction between both main effects [$F(4,19)=3.05$, $p<0.05$, $\eta=0.391$], which is illustrated in Fig. 4. The rate of respiration significantly increased from

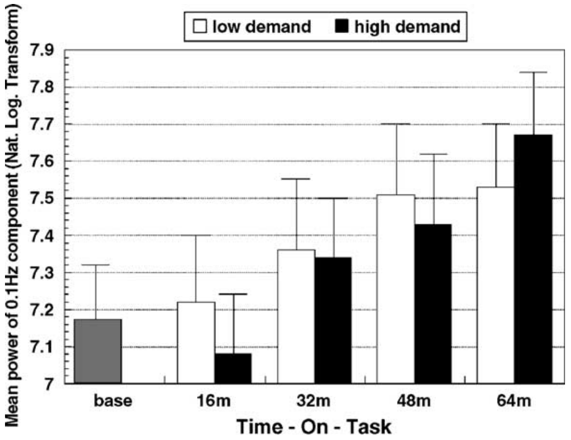

Fig. 3. Mean values and standard errors for power of mid-frequency component of heart rate variability (0.1-Hz sinus arrhythmia) across both high and low task demand and time-on-task (N=25).

baseline for the first 32 min of performance, but post-hoc tests revealed that this effect dissipated during the latter half of task activity (p<0.05). In addition, respiratory rate significantly increased during high demand relative to periods of low demand but only during the initial 32 min of performance (Fig. 4).

3.4. EOG

The EOG signal was quantified as both blink frequency in minutes and mean blink duration in milliseconds. A high number of movement artefacts in several data records meant that three participants were omitted from this analysis. A MANOVA was performed on both EOG variables that revealed a significant interaction between task demand×time-on-task×variable [Λ(4,24)=2.75, p<0.05 η=0.093].

The analysis of blink duration revealed significant main effects for both task demand [F(1,27)=12.20, p<0.01, η=0.311] and time-on-task [F(4,24)=46.98, p<0.01, η=0.798]. Blink duration was significantly suppressed during high demand compared to low demand (M=86.7 vs. 90.7 ms) and declined from baseline during task activity. The analysis of eye blink frequency revealed a significant interaction between workload and time-on-task [F(3,25)=2.73, p=0.05, η=0.092]. Post-hoc testing revealed that blink frequency was significantly reduced during episodes of high demand, but this effect was transient and only achieved significance during the initial 32-min period of performance.

3.5. Analyses of learning effect

Data from the MATB were transformed to produce a combined estimate of performance that afforded equal weighting to all three subtasks. Three dependent variables were selected to represent performance from each subtask (RMS error from tracking, mean reaction time from gauge monitoring, mean deviation from resource management) and these variables were subjected to a z-change score transformation, i.e., z-change=(score-mean group score at previous time period)/(standard deviation of group score at previous time period). Three z-change scores were calculated across the four 16-min time periods for both high and low task demand, i.e., T2–T1, T3–T2, T4–T3, and these z-change scores were averaged to yield a combined index of MATB performance. A positive change was equated with poorer performance relative to the previous period (i.e., increased RMS error, RT on gauge monitoring task, deviation on resource management) whereas negative change was evidence of learning. An ANOVA using these data revealed a significant interaction effect [F(4,22)=4.87, p<0.01, η=0.346] that indicated the presence of a sustained learning effect during the high demand condition only. This interaction is illustrated in Fig. 5.

A multiple regression analysis was performed to identify psychophysiological predictors of learning

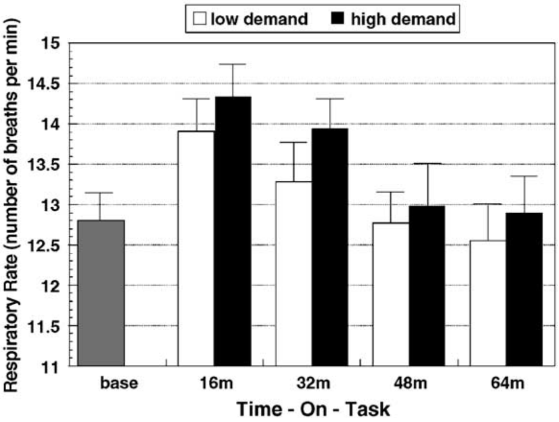

Fig. 4. Mean values and standard errors for respiratory rate across both high and low task demand and time-on-task (N=29).

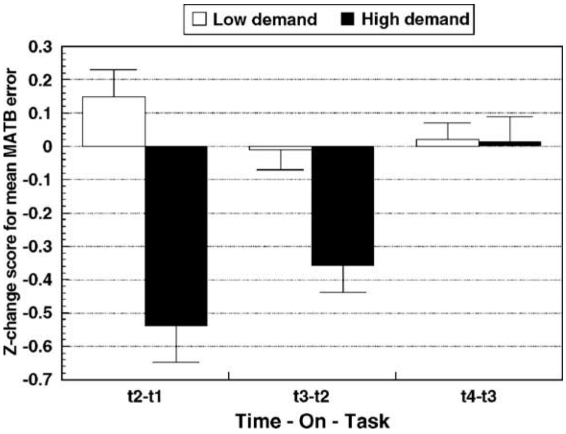

Fig. 5. Z-change score for MATB performance across time-on-task for high and low task demand (N=27). Note that a negative score indicates an improvement of MATB performance between successive periods, i.e., lower RMS error, faster mean RT, and lower deviation from target fuel level (N=28).

for the high demand condition only; the low demand condition was omitted from this analysis because of the absence of any consistent learning effect during this condition (Fig. 5). The presence of artifacts in the psychophysiological data and outliers in performance meant that only 20 participants were included in the regression analyses.

The following psychophysiological predictors were subjected to z-change score transformation prior to being entered into the multiple regression procedure: mean Θ power, mean α power, mean β power, mean IBI from ECG, mean power in mid- and high-frequency component of HRV (sinus arrhythmia and vagal tone, respectively), respiration rate, mean eye blink frequency, and duration. Three multiple regression analyses were performed (T2–T1, T3–T2, T4–T3), one outlier was removed from the first analysis and two were omitted from both subsequent analyses. The results of the multiple regression analyses with details of significant predictors are presented in Table 2.

The multiple regression analyses revealed that different psychophysiological variables functioned as predictors across time-on-task. During early learning (T2–T1), reduced IBI and sinus arrhythmia were associated with superior performance, i.e., reduced RMS, faster response times, reduced deviation from target fuel levels. This relationship between IBI and MATB performance was sustained during the middle period (T3–T2); however, increased vagal tone and eye blink rate were positive predictors of poor performance during this period. At the late phase of learning (T4–T3), the learning effect was nonexistent (Fig. 5) and only eye blink rate functioned as a significant predictor.

4. Discussion

The analyses of MATB performance revealed divergent trends between the three subtasks with respect to task demand. Performance on the tracking and resource management task (Fig. 1) declined when task demand was high. By contrast, accuracy on the gauge monitoring task increased during the high demand condition (Table 1). The relative decline of performance during low demand monitoring may

Table 2
Results of multiple regression analyses using psychophysiological variables to predict changes in performance over time-on-task for the high demand condition only (N=20)

	T2 (32 m)–T1 (16 m)			T3 (48 m)–T2 (32 m)			T4 (64 m)–T3 (48 m)		
	R^2=0.81 Adj R^2=0.62 F(9,18)=4.30 p=0.02			R^2=0.88 Adj R^2=0.74 F(8,17)=6.42 p<0.01			R^2=0.79 Adj R^2=0.54 F(8,17)=3.25 p=0.056		
Predictors	t	r^2	p	t	r^2	p	t	r^2	p
Inter-beat interval	−2.50	−0.64	.034	−2.57	−0.67	.033		N.S.	
Sinus arrhythmia	−2.51	−0.63	.032		N.S.			N.S.	
Vagal tone		N.S.		2.31	0.63	.050		N.S.	
Blink rate		N.S.		2.27	0.63	.053	2.24	0.62	.055

Note that r^2 refers to the partial correlation score.

have resulted from a failure to adjust response rates during the transition from high demand (an event rate of 30 deflections per minute) to low demand (an event rate of 2 deflections per minute). This explanation is likely as there was no explicit feedback during the transition from high-to-low demand and subjective expectancies of target frequency exert a crucial influence on participants' willingness to respond (Warm and Jerison, 1984).

Power in the Θ band from the sites Pz and P4 were the only EEG variables to differentiate between high and low task demand conditions. This pattern of Θ augmentation has characterised increased task demand in a number of earlier studies (Brooking et al., 1996; Fournier et al., 1999; Gevins and Smith, 2003; Gundel and Wilson, 1992). Increased Θ activity from frontal sites has been associated with increased demand and a state of focused attention (Gevins et al., 1998; Gundel and Wilson, 1992; Smith et al., 1999) but increased Θ at parietal sites was also shown to be sensitive to visuospatial sources of demand relative to a verbal source (Rugg and Dickens, 1982). The analyses of cardiovascular data revealed that mean IBI (heart rate) and vagal tone were sensitive to the task demand manipulation but not time-on-task. The sensitivity of heart rate to task demand was unsurprising, it is well known that sympathetic activation tends to accelerate heart rate under conditions of psychological challenge (Carroll et al., 1986; Furedy et al., 1996; Mathias and Stanford, 2003). However, the finding that heart rate reactivity was unaffected by time-on-task was unanticipated; an initial increase of heart rate often dissipates over sustained performance due to parasympathetic influence (Fairclough and Graham, 1999; Fairclough and Houston, 2004). The preservation of increased heart rate throughout task performance (which was characteristic of both task demand conditions) may reflect a dampening of parasympathetic influence due to the multitasking challenge of the MATB. This view was supported by the analysis of vagal tone which represents the parasympathetic influence of the vagus nerve on heart rate (Berntson et al., 1997; Porges, 1992, 1995). Our analyses revealed a suppression of vagal tone during task activity and this pattern was augmented during high task demand, i.e., decreased parasympathetic influence accounted for an increased heart rate during high demand activity (Berntson et al., 1991, 1994). The increase of task demand significantly reduced mean eye blink duration; this finding was expected, given that a high level of visual attention required for MATB performance and a suppression of blink duration represents one means of minimising visual occlusion.

It was hypothesised that psychophysiological sensitivity to task demand would be confounded by the learning effect over time-on-task. The suppression of α activity, which is associated with increased demand (Brooking et al., 1996; Fournier et al., 1999; Gevins and Smith, 2003; Klimesch, 1999), was a transient effect and α power was statistically indistinguishable from baseline levels after 48 min of performance (Fig. 2). An increase of α activity is synonymous with the reduction of cortical activation (Larson et al., 1998), which may be an indication of falling mental effort due to skill acquisition or task-related fatigue (Smith et al., 1999). The analyses of respiration rate and blink frequency revealed similar patterns, i.e., blink rate was suppressed and respiration rate increased during initial performance and both effects dissipated during the latter periods (Fig. 4). Increased respiration may reflect an initial period of anxiety provoked by early learning and task naivety; similarly, the suppression of blink rate activity may have also been a temporary characteristic of novice performance that receded as participants developed efficient strategies of visual search.

The participants performed both levels of demand over four consecutive periods and changes over time-on-task reflected a mixture of learning and task-related fatigue. Performance on the gauge monitoring and resource management subtasks both improved over time, e.g., faster response times, fewer misses (Table 1), reduced deviation from target level during the high demand condition (Fig. 1). However, performance on the tracking task grew progressively worse; this decline may indicate a strategic adjustment whereby participants sacrificed tracking accuracy in order to concentrate on the gauge monitoring and resource management tasks (Hockey, 1993, 1997). This interpretation is intuitive as tracking represented the least cognitively challenging subtask within the MATB.

The 0.1-Hz component of sinus arrhythmia is representative of the baro-reflex of the heart and this measure has been linked to mental effort and controlled processing (Hockey, 1997; Mulder, 1986).

Time-on-task was the principal influence on the 0.1-Hz component (Fig. 3), and this trend indicated a reduction of mental effort throughout task duration. In addition, the 0.1-Hz component was significantly suppressed during the initial period and augmented during the final period of high workload activity (Fig. 3). As the suppression of the 0.1-Hz component is associated with increased mental effort (Aasman et al., 1987; Mulder, 1979, 1985), it is suggested that mental effort peaked during early learning in the high demand condition (Fig. 3). This trend was reversed during the final period of performance (Fig. 3) when mental effort was reduced, either as deliberate response to conserve effort in response to high demand (Hockey, 1997) or as an unintentional consequence of mental fatigue. This pattern was peculiar to this variable and it is possible that the 0.1-Hz component represented a unique aspect of psychophysiological activity during skill acquisition.

Several variables (Θ activity at Pz and P4, heart rate, vagal tone, eye blink duration) were sensitive and diagnostic with respect to task demand, i.e., these variables distinguished between high and low demand while remaining insensitive to the influence of time-on-task. Other variables demonstrated a transient sensitivity to task demand during the early period of performance which was compromised by skill acquisition or the presence of task-related fatigue, e.g., α power, 0.1-Hz component of HRV, respiration rate, blink frequency. This latter group were less diagnostic but much of this definition depends upon the independent variable under investigation. For instance, the former group would be useless for research on the process of skill acquisition; similarly, the sensitivity of the latter group to task would be inadequate for a study of cognitive demand.

The analysis of learning effects demonstrated a consistent reduction of MATB error during the high demand condition only (Fig. 5). This was unsurprising as the combination of high temporal demands and multitasking provided considerable potential for skill acquisition and the development of strategy, which was minimal in the low demand condition. The regression analyses (Table 2) were conducted on twenty from the original thirty participants and so these results should be considered with caution. It was apparent that psychophysiological predictors of learning changed over the course of the learning curve (Table 2). During early learning (T2–T1), a reduction of MATB error was predicted by increased heart rate and a suppression of the 0.1-Hz component of sinus arrhythmia; this period represented the most demanding and effortful phase of learning and those participants with high sympathetic activation (i.e., accelerated heart rate) who invested mental effort achieved the greatest improvement of performance. The predictive quality of heart rate persisted into middle period of learning (T3–T2; Table 2) where both increased vagal tone and blink frequency were associated with increased MATB error. Vagal tone is a parasympathetic marker (Porges, 1992, 1995) and this finding indicated that increased parasympathetic inhibition was associated with increased error, i.e., sympathetic activation of the ANS was important for learning. The association between MATB error and increased blink rate may be due to the incompatibility between the level of visual occlusion produced by a high blink rate and the visual demands of the multitasking MATB environment. This association represented the only significant predictor during the late phase of learning (T4–T3), but at this point, performance had reached asymptote and learning was minimal (Fig. 5).

A major weakness of the study concerned the contradictory learning effects within the MATB environment. In the first instance, performance on the tracking subtask declined with time-on-task, so evidence of learning was not found for all MATB subtasks. Secondly, evidence for learning was mixed on the gauge monitoring task; the analysis of reaction times showed an improvement with increased practice, however, the number of false alarms continued to rise in parallel (Table 1). This confusion may be due to the ambiguous nature of the time-on-task manipulation, which provided an opportunity to practice and learn whilst provoking task-related fatigue during the latter periods of task activity.

The notion of mental effort as energy mobilisation (Fairclough and Houston, 2004; Gaillard and Wientjes, 1994) found mixed support. The initial suppression of α power in the EEG combined with the reduction of power in the 0.1-Hz component were indicative of effortful information processing as participants devised strategies to improve performance during early learning. However, this was not a universal pattern and several variables such as heart rate failed to respond to time-on-task. This dissociation begs an old question about the distinction between psychophysiological indicators of mental effort and general activation in the ANS (Beatty, 1982). As the reduction of mental effort is a central feature of skill acquisition and high demand is characterised by increased effort, it would be prudent to operationalise mental effort using only those variables that were sensitive to both independent variables.

5. Conclusions

The starting point for the study was an assumption that the sensitivity of psychophysiological variables to task demand may be jeopardised by skill acquisition. This hypothesis was supported by several variables such as respiration rate and eye blink frequency but not others, e.g., heart rate, vagal tone. The latter group is characterised as diagnostic measures of task demand; the former category of variables is less diagnostic but demonstrated sensitivity to both independent variables.

The psychophysiological response to task demand may be characterised in terms of a short-term effect during early learning and a sustained response following 30 min of practice. This short-term effect represents effortful processing (suppression of the 0.1-Hz component), increased catabolic activity (increased respiration), and higher levels of electrocortical activation (suppression of α power). This effect dissipated due to the influence of time-on-task, but it was difficult to identify which component of sustained performance was responsible, i.e., skill acquisition or task-related fatigue. The sustained response to task demand was typified by a reduction of parasympathetic inhibition (reduced vagal tone and increased heart rate), reduced eye blink duration, and an increase of Θ activity from parietal sites. This sustained response may represent the state of focused concentration that was necessary to perform a complex, multitasking activity.

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