Psychophysiological predictors of task engagement and distress

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Abstract

Biocybernetic systems utilise real-time changes in psychophysiology in order to adapt aspects of computer control and functionality, e.g. adaptive automation. This approach to system design is based upon an assumption that psychophysiological variations represent implicit fluctuations in the subjective state of the operator, e.g. mood, motivation, cognitions. A study was performed to investigate the convergent validity between psychophysiological measurement and changes in the subjective status of the individual. Thirty-five participants performed a demanding version of the Multi Attribute Test Battery (MATB) over four consecutive twenty-minute blocks. A range of psychophysiological data were collected (EEG, ECG, SCL, EOG, respiratory rate) and correlated with changes in subjective state as measured by the Dundee Stress State Questionnaire (DSSQ). The DSSQ was analysed in terms of three subjective meta-factors: Task Engagement, Distress and Worry. Multiple regression analyses revealed that psychophysiology predicted a significant proportion of the variance for both Task Engagement and Distress but not for the Worry meta-factor. The consequences for the development of biocybernetic systems are discussed.

Introduction

Biocybernetic systems utilise real-time changes in psychophysiology as an adaptive control input to a computer system. For example, a biocybernetic loop may control the provision of automation within an aviation environment (Byrne & Parasuraman, 1996). This loop diagnoses the psychological status of the human operator based on psychophysiological activity and relays a control signal to initiate or relinquish system automation (Pope, Bogart, & Bartolome, 1995). The affective computing concept (Picard, 1997) represents an example of the same principle where psychophysiological monitoring/diagnosis enables computer software to respond to the subjective state of the user. The concept of biocybernetic control enables a wide range of applications (Allanson & Fairclough, 2004), from adaptive automation (Scerbo et al., 2001) to health-monitoring (Gerasimov, Selker, & Bender, 2002) and biofeedback training tools (Pope & Palsson, 2001).

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The goals of biocybernetic control are to promote safe and effective performance, as well as curtailing “hazardous states of awareness” (Prinzel, 2002), such as: fatigue, anxiety, boredom. Both goals are linked as hazardous states are often incompatible with reliable and adequate performance; in addition, states related to poor performance such as anxiety may have consequences for the health of operator.

The biocybernetic control loop may be designed in one of two ways: to promote positive/effective performance states or to avoid negative/ineffective states (Scerbo, 2003). Freeman et al (1999) used an EEG-based index of engagement (Pope et al, 1996) to drive a biocybernetic loop that worked on the basis of a negative control loop, i.e. system automation was only activated if participant was deemed to be engaged with the task, and the system automatically reverted to a manual mode if participants’ level of automation declined. Therefore, the system was designed to maintain participants in a stable and moderate level of task engagement, thus avoiding operator complacency during system automation (Parasuraman & Riley, 1997) whilst allowing the user to experience the benefits of automation, e.g. reduced mental workload, stress, and fatigue.

The promotion of positive states such as task engagement and avoidance of negative moods such as distress and anxiety is central to biocybernetic control. However, these systems are reliant on the sensitivity and diagnosticity of psychophysiology to detect positive and negative states (Fairclough & Venables, 2004). On the one hand, the psychophysiological response appears sufficiently differentiated to discriminate broad patterns of emotional response (both positive and negative). On the other hand, it is difficult to formulate the psychophysiological signature of each subjective state with the required degree of precision, as demonstrated by inconsistent findings in this area (Cacioppo, Klein, Berntson, & Hatfield, 1993). This disparity may stem from two sources: the inclusiveness of the psychophysiological response, and the multifaceted experience of subjective states. Whenever the psychophysiological signature of a performance state is captured, it contains a non-affective content (e.g. cognitive demands, motor activity) and a contextual element triggered by the functional goals associated with that emotion (e.g. approach or avoidance) as well as an emotional signature (Stemmler, Heldmann, Pauls, & Scherer, 2001). This lack of specificity is mirrored by the experience and operationalisation of subjective states, which may involve a complex interplay between affective feelings, motivational desires and related cognitions (Matthews et al., 2002).

A partial solution to this problem is to adopt an inclusive definition of the subjective state encompassing affective, motivational and cognitive dimensions of subjective experience as well as the psychophysiological response. This was the logic underlying the development of the Dundee Stress State Questionnaire (DSSQ, Matthews et al., 2002) that attempts to integrate aspects of subjective experience within a number of meta-factors. The DSSQ was derived via factor analysis of self-report questionnaires from a large sample (e.g. Fenigstein, Scheier, & Buss, 1975; Heatherton & Polivy, 1991; Matthews & Desmond, 1998; Matthews, Jones, & Chamberlain, 1990; Sarason, Sarason, Keefe, Hayes, & Shearin, 1986). The factor analysis yielded three factors, each of which encompass at least three sub-scales:

Task Engagement (energy, concentration, motivation), Distress (tension, negative affect, confidence) and Worry (self-focus, self-esteem, cognitive interference). Task Engagement was defined as an "effortful striving towards task goals" (Matthews et al., 2002; Matthews et al., 1997), this factor increased during a demanding working memory task and declined when participants performed a sustained vigilance task (Matthews et al., 2002). The Distress meta-factor was characterised by "an overload of processing capacity" (Matthews et al., 2002; Matthews et al., 1997) and tended to increase when participants experienced a loss of control over performance quality (Matthews et al., 1997). The third Worry meta-factor was concerned with rumination and negative self-evaluation (Matthews et al., 2002; Matthews et al., 1997) and is based upon the S-REF model of anxiety (Wells & Matthews, 1996); the Worry factor was also found to increase when participants experienced a loss of control over performance (Matthews et al., 1997).

This study was performed to investigate whether psychophysiology could be used to predict positive (Task Engagement) and negative (Distress, Worry) performance states. Participants were exposed to a demanding task over a sustained time period. The high level of demand was included to provoke Task Engagement whilst the time-on-task manipulation was intended to eventually reduce engagement whilst inflating Distress and Worry.

Method

Participants

Thirty-five university students participated in the experiment, (13 female and 22 male), and all received a monetary reward. The age of participants ranged from 18-40 years, (M = 24.1 years, S.D. = 5.90). Potential participants were excluded if they were pregnant, on medication or reported any known cardiovascular problems. Participants were additionally requested not to consume large amounts of alcohol the night before, nor drink large amounts of caffeine or participate in strenuous exercise on the morning of the experiment.

Experimental task

The computer task used for the experiment was the Multi-Attribute Task Battery (MATB, Comstock & Arnegard, 1992), this is a multitasking environment containing three subtasks: tracking, system monitoring, and fuel resource management. Each subtask was pre-scripted to a high level of task demand (the parameters of which were tested and utilised in a prior experiment (Fairclough & Venables, 2004).

Psychophysiological variables

EEG was recorded with Ag/AgCl electrodes, across the four sites utilised by Pope et al. (1995) study: Cz, P3, Pz, P4, (with a ground site located midway between Cz and Pz). Each site was referenced to the left and right mastoid areas. The EEG signals were amplified (using four BIOPAC EEG100C differential, bio-electric potential modules). The high and low bandpass filters were set at 0.1Hz and 35Hz, respectively. The EEG signals were analysed via Fast Fourier Transform (FFT) in steps of 2.65 s with an overlap of 0.5 s. Epochs with total power exceeding 200% of the average for that participant were identified as outliers and removed from subsequent analysis, i.e. a pilot exercise found this criterion to be highly associated with artifacts in the EEG record identified by visual inspection. Mean % power values were obtained for: θ (4.3 – 7.8Hz), α (8.2 – 12.9Hz), and β (13.3 – 21.9Hz).

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 0.05-35Hz, and amplified by a BIOPAC EOG100C differential, (high gain), corneal-retinal potential amplifier. Eye-blink frequency and duration were the parameters derived from a smoothed EOG signals.

Heart rate activity was recorded using a standard Lead II configuration, and amplified using vinyl electrodes positioned on the 7th intercostal space on the right and left side of the body. A common ground electrode was placed on the sternum. ECG was measured using a BIOPAC TEL 100C differential (high gain) amplifier. The high and low bandpass filters were set at 0.5-35Hz, respectively. R peaks of the ECG were detected offline, and the interbeat interval (IBI) between successive R waves was calculated. These data were evaluated for missed and ectopic beats, the former were corrected via interpolation and the latter were discarded. HRV in mid- (0.09-0.13Hz) and high- (0.14-0.40Hz) frequency bands were calculated from the IBI data by means of an FFT analysis with Carspan software (L.J.M Mulder, van Roon, & Schweizer, 1995).

Respiration was monitored using two elasticated belts placed around the chest and diaphragm. Respiration signals were again amplified using a (differential, high gain) BIOPAC TEL100C remote monitoring module, with the filter settings at 0.05-35Hz. The waveform signals of both chest and diaphragm expansion were added together using BIOPAC AcqKnowledge software, and peaks from the combined signal were detected and used for the calculation of respiration rate (i.e. breaths per min).

Skin Conductance Level (SCL) was measured with two electrodes (which produce a continuous voltage electrode excitation of 0.5 V), attached to the side of the foot (Boucsein, 1992). These signals were amplified using a BIOPAC TEL100C remote monitoring module, and subsequently filtered (low pass) at 1Hz to rid of extraneous noise. Skin conductance values for mean and area were collected every 2secs and averaged over 4min periods. The sample rate for all channels (i.e. EEG, ECG, SCL, EOG, and Respiration) was 500Hz.

Subjective measures

Subjective state was measured using the Dundee Stress State Questionnaire (DSSQ, Matthews et al., 2002; Matthews et al., 1997). This battery of questionnaires containing Likert scales derived from earlier research which have been grouped into three fundamental meta-factors: Task Engagement, Distress and Worry.

Task Engagement is concerned with “a commitment to effort” (Matthews et al., 2002, p. 335) and contains scales for: energetical arousal (alert-tired, i.e. a mood adjective checklist, participants were asked to describe how well each adjective described how they felt at that moment on a 4-point scale from “definitely” to “definitely not”, Matthews et al., 1990), motivation (8 items regarding on level of mental effort and feelings about success/failure assessed on a 9-point Likert scale) and concentration (7 items regarding the perceived efficiency of concentration assessed on a 5-point Likert scale, Matthews & Desmond, 1998). The theme of those scales grouped under the Distress meta-factor is “an overload of processing capacity” (Matthews et al., 2002, p. 336). This factor contains scales for: tense arousal (tense-relaxed) and hedonic tone (5-point Likert scale, sad-happy, both items were assessed using the mood adjective checklist described previously for energetical arousal, Matthews et al., 1990) as well as confidence/perceived control (6 items relating to positive aspects of performance and perceived control assessed via a 5-point Likert scale, Matthews & Desmond, 1998). The third meta-factor of the DSSQ is Worry and this factor is concerned with self-evaluation and self-focus; the Worry factor contains scales pertaining to: self-focus (8 items assessed via a 5-point Likert scale related to private self-consciousness, Fenigstein et al., 1975), self-esteem (a 5-point Likert scale was used to assess 6 items related to social self-esteem and 1 item relating to performance self-esteem, Heatherton & Polivy, 1991) and cognitive interference (8 items to assess the frequency of task-relevant thoughts and 8 items to assess the frequency of task-irrelevant thoughts both assessed via 5-point Likert scale from “never” to “very often”, Sarason et al., 1986).

Full details regarding the factor structure of the DSSQ, population norms and state responses to different types of psychological tasks may be found in (Matthews et al., 2002).

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 fifteen-minute 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.

Following the baseline period, participants were presented with a 5min training session to acquaint themselves with the keyboard/joystick controls. This was followed by a 20min high-demand practice block. Participants then began the formal task session of 4 x 20min (high-demand) blocks of MATB performance (80mins in total), i.e. a repeated measures design. The participants received no information about the duration of the experimental task prior to the formal task (i.e. the participants did not know how many 20min blocks must be completed); in addition, participants were asked to surrender their watches to remove anticipation of task completion. Prior to the practice block, and again after each task block, participants were presented with a computerised version of the DSSQ. The DSSQ asked participants to rate their feelings and moods as perceived *during task performance*. The DSSQ took between three and five minutes to complete. Upon completion, participants persisted with the next task block. This continued until all four blocks had been completed. The recording of the physiological measures was initiated at the same time as each task session was started.

Results

Experimental data were analysed using Statistica 6.1 (Statsoft Inc.). Outliers (defined as values lying at least three standard deviations outside the group mean) were excluded from all analyses. Significant MANOVA findings are expressed using Wilks' Lambda (Λ) and data for effect size (η^2) are also provided for additional information.

The effect of Time-On-Task on MATB performance

A MANOVA was performed on MATB performance (tracking error, accuracy on system monitoring task, mean deviation of fuel management task) over four blocks of twenty minutes. There were no significant changes in performance over time, i.e. MATB performance was stable throughout the test session. Mean values for MATB performance throughout the session were: RMS error (M = 70.31, s.d. = 3.06), target detection as percentage (M = 81.7, s.d.=2.97), and deviation from target fuel level (M = 151.48, s.d. = 36.16).

The effect of Time-On-Task on subjective states

Nine scales from the DSSQ were divided into three groups based on the factor analysis reported in (Matthews et al., 2002). This categorisation divided the DSSQ into three meta-factors: Engagement (energetical arousal, motivation, concentration), Distress (tense arousal, hedonic tone, confidence), and Worry (self-focus, self-esteem, task-irrelevant thoughts). The z-change score from each scale of the DSSQ was calculated where: *zchange = (score – group_mean from previous time period) / standard deviation of group from previous time period*. This transformation is based upon the one reported by Temple et al. (2002) and is intended to standardise change scores across all DSSQ scales.

The transformed values from those three scales associated with the Task Engagement meta-factor were analysed via a 3 x 4 MANOVA (DSSQ scale x Time-On-Task). This analysis revealed an interaction effect of marginal significance [Λ (6,29) = 0.763, $p = 0.06$, $\eta^2 = 0.321$]. Mean values for each component of the Task Engagement meta-factor are shown in Table 2. Post-hoc Bonferroni analyses revealed that energetical arousal showed a large decrement after 40 minutes of performance compared to other periods ($p < 0.01$). Similarly, motivation levels fell at a higher rate during the first half of performance compared to later periods ($p < 0.01$). The decrement associated with Concentration was reduced during the final period of performance compared to previous periods ($p < 0.01$).

The 3 x 4 MANOVA for the Distress meta-factor revealed a significant main effect for time-on-task [Λ (3,32) = 0.69, $p < 0.05$, $\eta^2 = 0.253$]. Both tense arousal and hedonic tone exhibited negative and positive change scores over time, but the magnitude of these changes were insignificant. Post-hoc Bonferroni testing revealed a significant effect for only the confidence factor, which declined sharply during the final twenty minutes of performance ($p < 0.05$).

A 3 x 4 MANOVA was conducted on the three components of the Worry meta-factor. This analysis revealed a significant interaction effect only [Λ (6,29) = 0.75, $p < 0.02$, $\eta^2 = 0.382$]. Post-hoc analyses of the DSSQ scales indicated that self-esteem showed a significant increase after forty minutes of performance ($p < 0.01$). In addition, the rate of task-irrelevant thoughts was highest after twenty and sixty minutes compared to the remaining time periods ($p < 0.01$).

Multiple Regression analyses

Psychophysiological data were standardised using a z-change score transformation (described in the previous section) prior to regression analyses. The z-change transformation was performed on psychophysiological data averaged over the final five minutes of each twenty minute period of task performance: this period was selected to achieve maximum coherence with the subjective self-report scales (i.e. participants were asked to report how they felt at that moment), which were administered at the end of each twenty minute period.

The transformed psychophysiological data were averaged across all four time periods and subjected to a correlation analysis. This analysis was performed to estimate the degree of redundancy between different psychophysiological measures and to identify variables for inclusion in the regression analyses. A probability level of < 0.10 was used for this analysis in order to identify both moderate as well as high levels of correlation. Based on this correlation, five psychophysiological variables with low levels of inter-item correlations were selected as independent variables for the multiple regression analyses; these variables were alpha power in the EEG (α, averaged across all four sites), inter-beat interval of the heart rate (IBI), 0.1Hz component of sinus arrhythmia (SA), respiration rate (RR) and rate of eyeblink frequency (BR).

The variables from the DSSQ were averaged into three meta-factors described by Matthews et al (2002): Task Engagement, Distress and Worry. Task Engagement was calculated by combining z-change scores from three DSSQ components: Energetical Arousal, Concentration and Motivation. To calculate the Distress factor, z-change scores for Hedonic Tone and Confidence/Control were reversed and combined with the z-change score for Tense Arousal; therefore, increased Distress was represented by rising tension in combination with negative affect and falling confidence. The Worry factor involved a combination of z-change scores for Frequency of Task-Irrelevant Thoughts and Self-Focus in conjunction with a reversed score for Self-Esteem, i.e. Worry = increased cognitive interference and self-focus in conjunction with falling self-esteem. The rationale for these formulations may be found in Matthews et al (2002).

A series of multiple regressions were performed to investigate if Task Engagement , Distress and Worry were predicted by psychophysiological variables. Four multiple regression analyses were conducted for each meta-factor using data from each period of performance. The results of the Task Engagement analysis are presented in Table 1.

Table 1. Results of the multiple regression using psychophysiological predictors of the DSSQ meta-factor Task Engagement (N=33). A summary of the regression is provided in the upper panel and significant predictors are listed in the lower panel with their Beta weights and partial correlations in brackets. Note: RR = respiration rate, BR = eye blink rate, SA = 0.1Hz component of sinus arrhythmia, α = EEG alpha power

	20min		40min		60min		80min	
Regression	Adj. $R^2 = 0.32$ $F(5,30)= 3.82$ $p < 0.01$		Adj. $R^2 = 0.43$ $F(5,30)=5.20$ $p < 0.01$		Adj. $R^2 = 0.41$ $F(5,30)=4.98$ $p < 0.01$		Adj. $R^2 = 0.53$ $F(5,30)=7.62$ $p < 0.01$	
Significant Predictors $p<0.05$	RR	0.57 [.59]	RR	0.69 [.69]	RR	0.32 [.40]	RR	0.47 [.55]
					α	-0.62 [-.63]	α	-0.66 [-.69]
					SA	-0.34 [-.40]	SA	-0.35 [-.42]
							BR	-0.31 [-.42]

The regression analyses revealed a statistically significant relationship between Task Engagement and psychophysiological variables, which was sustained throughout the period of task performanced. Psychophysiological variables predicted between 32 and 53% of the variance associated with Task Engagement. The most consistent predictor of Task Engagement was respiration rate which had a positive relationship with Task Engagement. Mean power in the α bandwidth, the 0.1Hz component of sinus arrhythmia and eyeblink frequency exhibited a negative relationship with Task Engagement during the latter periods of the task activity.

Table 2. Results of the stepwise regression using psychophysiological predictors of the subjective meta-factor Distress (N=35). A summary of the regression is provided in the upper panel and significant predictors are listed in the lower panel with their Beta weights and partial correlations in brackets. Note: SA = 0.1Hz component of sinus arrhythmia, α = EEG alpha power

	20min		40min		60min		80min	
Regression	Adj. $R^2 = 0.26$ $F(5,30)=2.87$ $p < 0.05$		Adj. $R^2 = 0.42$ $F(5,30)=5.26$ $p < 0.01$		Adj. $R^2 = 0.42$ $F(5,30)=5.31$ $p < 0.01$		Adj. $R^2 = 0.38$ $F(5,30)=4.51$ $p < 0.01$	
Significant Predictors $p<0.05$	α	0.36 [.34]	α	0.38 [.46]	α	0.67 [.66]	α	0.64 [.63]
			SA	0.72 [.68]	SA	0.57 [.59]		

The results of the stepwise regressions on the Distress meta-factor are presented in Table 2. Psychophysiological variables predicted between 28 and 42% of the variance associated with Distress. It was apparent that both α activity from the EEG and the 0.1Hz component of sinus arrhythmia had a positive relationship with levels of Distress. None of the psychophysiological predictors achieved statistical significance during the multiple regression to predict the Worry meta-factor. This pattern of null findings was repeated across all four periods of task performance for the Worry meta-factor.

Discussion and conclusions

The experimental manipulations of high task demand and sustained performance had no significant affect on task performance, but caused a number of latent changes (Hockey, 1997) with respect to psychophysiology and subjective self-report. The DSSQ data were analysed as change scores to represent time-on-task trends relative to the previous period of task performance. Two components of Task Engagement, energetical arousal and motivation, showed a significant decline during the first forty minutes of performance only and falling levels of concentration accounted for the decline of Task Engagement during the latter half of the task period. The influence of time-on-task on the Distress factor was modest by comparison. The combination of high task demand and sustained performance failed to significantly increase tense arousal or induce negative affect via the hedonic tone factor; however, it was significant that confidence levels fell dramatically after the final period of performance. The sudden decline of confidence suggests that participants had reached the limits of successful coping after the fourth session (participants were not told when the task would end) and Distress may have been augmented if the task period had been extended. The Worry meta-factor was also relatively unaffected by the experimental task. The frequency of task-irrelevant thoughts increased with each period of performance; therefore participants had more difficulty focusing attention on the task as time progressed. The significant increase of self-esteem after forty minutes of performance was unexpected and is assumed to represent a perception of increased task mastery. The absence of any significant effect on self-focus was anticipated; the high temporal demands associated with multitasking MATB performance discourage rumination or a shift of attention from the task to the self (Matthews et al., 2002).

The main goal of the study was to investigate whether psychophysiological measures could predict changes in subjective states as represented by the DSSQ. The multiple regression analyses (Tables 1 and 2) provided some support of predictive validity, but with several important caveats. Psychophysiological variables predicted between one third and half of the variance associated with the Task Engagement meta-factor over the four periods of performance (Table 1). Respiration rate was a consistent, positive predictor of engagement, i.e. higher breathing rate = increased Task Engagement. A number of other variables made a significant contribution to the regression equation during the latter periods of performance (Table 1). Suppression of both α activity and the 0.1Hz component were associated with Task Engagement, both of which have been associated with increased mental effort (Gevins et al., 1998; Mulder, 1986). This finding suggests that covariation between psychophysiology and subjective self-report may be moderated by changes in sympathetic activation related to the investment of mental effort. The general pattern of the Task Engagement regression was an accumulation of psychophysiological predictors with increased time-on-task; for instance, a suppression of eye blink frequency was also associated with Task Engagement during the final period of performance (Table 1). This pattern may be indicative of increased mental effort as a compensatory strategy to counteract the influence of fatigue on performance (Hockey, 1997).

The prediction of the Distress meta-factor was modest during the initial period of performance (Table 2). This multiple regression presented a positive association between Distress and both the 0.1Hz component and α activity (Table 2). The Distress factor represents "an overload of processing capacity" (Matthews et al., 2002); in the context of the current study, any overload of capacity was induced by a failure to sustain performance over time-on-task. The effect of task activity was to suppress the level of α activity, which has been associated with mental effort investment (Gevins et al., 1998), and the Distress factor was associated with a failure to sustain α suppression. The positive association with the 0.1Hz component indicated that Distress was associated with a tendency to reduce or conserve mental effort (Hockey, 1997), i.e. the 0.1Hz component is suppressed when mental effort is invested. Therefore, the Distress meta-factor was associated with a "giving up" pattern from the psychophysiological domain.

None of the psychophysiological measures used in the study could successfully predict the Worry meta-factor. This null finding may stem from the failure of the independent variables to induce Worry in the participants. In addition, the Worry meta-factor is characterised by attentional/cognitive scales and it is possible that the psychophysiological variables used in the study failed to tap this cognitive dimension. The Worry meta-factor may have been predicted by measures of cognitive psychophysiology such as evoked-cortical potential variables, e.g. the P300 component (Prinzel et al., 2003).

The current study had at least one major weakness concerning the range of psychophysiological variables used during the study, which excluded several important measures such as blood pressure and facial EMG. The former has been used to differentiate states of challenge and threat (Blascovich & Tomaka, 1996; Tomaka, Blascovich, Kibler, & Ernst, 1997); two states that bear a resemblance to the DSSQ concepts of Task Engagement and Distress used in the current study. Facial EMG has demonstrated consistent changes in response to pleasant and unpleasant stimuli; particularly in the corrugator muscles above the eyebrow (Cacioppo, Bush, & Tassinary, 1990) and EMG activity from these sites has been used to differentiate between positive and negative affect (Bradley, Cuthbert, & Lang, 1996). The inclusion of these measures may have increased the explanatory power of the regression analyses if blood pressure and facial EMG provide a unique contribution to the variance of the subjective measures . The regression analyses indicated that psychophysiology explained between twenty-six and fifty-three percent of variance in the subjective states data (Tables 1 and 2), the average was approximately forty per cent, leaving more than half the variance unexplained. Future research could investigate how to improve the explanatory power of regression analyses by supplementing psychophysiology with other data sources, e.g.

real-time performance, cognitive models. For example, individual traits such as age and personality may play a role in the prediction of subjective states. The influence of both coping style and neuroticism on Distress from the DSSQ has been demonstrated (Matthews et al., 2002) and other more transitory variables such as sleep quality and time-of-day may also play a role.

Task Engagement and Distress are relevant dimensions of subjective state for biocybernetic control as both have implications for performance and the wellbeing of the human operator. The current study operationalised engagement and Distress using the meta-factors devised by Matthews et al (1997, 2002) which integrate mood, motivation and cognition within unitary factors. This level of specificity is sufficient to represent the subjective state of the operator as a two-dimensional space and construct a biocybernetic loop designed to counteract low levels of Task Engagement and high Distress. This characterisation should suffice for many applications where performance is important such as adaptive automation, computer games and educational software. However, this level of specificity will not suffice for those biocybernetic systems that require a more detailed level of mapping, e.g. between distinct emotional states and psychophysiology.

The rationale underlying the development of biocybernetic control is that these systems can deliver timely and intuitive system interventions. The fact that psychophysiology was capable of explaining a substantial amount of the variance associated with both Task Engagement and Distress in the current study provides momentum for the continued development of these systems. However, it is difficult to predict how this degree of convergent validity will translate into operators' perceptions of system reliability and influence related variables such as trust. A detailed understanding of how the mapping between psychophysiology and the subjective state influences user perceptions of biocybernetic control is a topic for future research.

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