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Prediction of subjective states from psychophysiology: A multivariate approach

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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 Task Battery (MATB) over four consecutive 20-min blocks. A range of psychophysiological data were collected (EEG, ECG, skin conductance level (SCL), EOG, respiratory rate) and correlated with changes in subjective state as measured by the Dundee Stress State Questionnaire (DSSQ). MATB performance was stable across time-on-task; psychophysiological activity exhibited expected changes due to sustained performance. The DSSQ was analysed in terms of three subjective meta-factors: Task Engagement, Distress and Worry. Multiple regression analyses revealed that psychophysiology predicted a substantial 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.

Keywords: EEG; ECG; Respiration; Subjective states; Mood

1. 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 and 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 et al., 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. It is envisaged that interaction with an "affective computer" will be interactive and intuitive, providing help when frustration is diagnosed or increasing the difficulty level of a computer game if the user is deemed bored or disinterested. The concept of biocybernetic control enables a wide range of applications (Allanson and Fairclough, 2004), from adaptive automation (Scerbo et al., 2001) to health-monitoring (Gerasimov et al., 2002) and biofeedback training tools (Pope and Palsson, 2001).

The use of psychophysiology to control system automation has a number of advantages over performance-based methods of monitoring the operator (Byrne and Parasuraman, 1996): (a) psychophysiology provides a continuous stream of data input whereas performance input may be discrete, (b) a performance-based diagnosis may not be available if the system is fully automated and (c) performance quality is relatively insensitive to implicit changes in user state which may be indexed via psychophysiology (O'Donnell and Eggemeier, 1986). This latter point is important as the sensitivity of biocybernetic control is based upon the capacity of these systems to monitor covert processes of psychophysiological regulation.

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The model of mental effort regulation proposed by Hockey (1993, 1997) captures this divergence between overt performance and covert changes in psychophysiological state. Within this framework, stable levels of performance may mask latent decrements that represent a covert process of mental effort regulation. Latent decrements include qualitative changes in performance strategy in conjunction with ‘‘compensatory costs’’ such as increased sympathetic activation of the ANS and negative affect, e.g. anxiety. There are numerous examples of these compensatory costs in response to increased task difficulty/psychological challenge. For instance, catabolic changes in the sympathetic nervous system instigate an orchestrated patterns of physiological activity, including: accelerated heart rate (Mathias and Stanford, 2003; Tomaka et al., 1997), increased systolic blood pressure (Blascovich et al., 1999; Suzuki et al., 2003), a rise of electrodermal activity (Gendolla and Krusken, 2001), a fast/shallow respiratory pattern (Boiten, 1998) and reduced eye-blink duration in conjunction with increased blink frequency (for predominantly visual tasks) (Veltman and Gaillard, 1996, 1998). Corresponding data are available from the subjective domain: students taking a college examination reported mood changes (e.g. increased fear and anxiety) compared to a typical day in class (Thayer, 1967). Similarly, participants exposed to high mental workload reported falling energy levels and negative affect in combination with increased tension (Matthews et al., 1990).

The goal of the biocybernetic control system is to operationalise psychological states via a ‘‘signature’’ pattern of psychophysiological activity. For instance, Pope et al. (1995) collected spontaneous EEG activity during the performance of a task, analysed these data into several ratio measures and selected one to represent the level of operator engagement associated with the task. This index captured the ratio of high-frequency EEG activity (β) to a combination of lower-frequency components ($\Theta + \alpha$). This EEG-based engagement index was used to drive biocybernetic control of adaptive automation in a laboratory study (Prinzel et al., 1995), i.e. system automation was only available if the operator was deemed engaged with the task. Further experiments with the same system demonstrated benefits in performance quality as well as reduced mental workload (Freeman et al., 1999; Prinzel et al., 2000). These positive findings have been replicated using prolonged periods of task performance (Freeman et al., 2000) and a vigilance task (Milkulka et al., 2002); for a recent summary of this research, see Scerbo et al. (2003).

The utility of biocybernetic control depends on a close association between psychophysiological activity and those subjective states that are relevant for task performance, e.g. engagement, anxiety, anger, boredom (Prinzel, 2002). The problem of mapping from psychophysiology to subjective experience and vice versa has direct implications for the introduction of biocybernetic control systems. The goal of the biocybernetic loop is to make system interventions that appear both timely and intuitive to the user. These qualities are important indicators of system reliability, which is an important determinant of trust in an automated system (Moray et al., 2000; Muir, 1994; Muir and Moray, 1996). Therefore, it is important that psychophysiological triggers for system intervention have a coherent and consistent relationship with the subjective state of the user.

There is evidence of convergent validity between psychophysiology and mood states from previous research. For example, Thayer (1970) reported a significant correlation between a psychophysiological composite (heart rate + skin conductance) and a bipolar scale of general activation (lively–quiet). This finding was replicated by Matthews et al. (1990) who reported that skin conductance level was correlated with energy, whilst a composite variable (skin conductance + heart rate) was associated with tension. The search for psychophysiological predictors of emotional experience represents a similar line of investigation. A field study using ambulatory measures of blood pressure and heart rate found that both variables increased with the intensity of negative moods but were insensitive to positive affective states (Shapiro et al., 2001). Christie and Friedman (2004) measured psychophysiology during exposure to film clips designed to induce positive and negative emotional responses. These authors extracted two discriminant functions to describe the ANS response: an ‘‘activation’’ factor and an ‘‘approach–withdrawal’’ factor. Both ANS factors were combined to create a multivariate space wherein anger and amusement were distinguished on the ‘‘activation’’ scale, whilst anger and fear differentiated on the ‘‘approach–withdrawal’’ scale.

The psychophysiological response appears sufficiently differentiated to discriminate broad patterns of emotional response as well as quantitative fluctuations in mood. However, it is difficult to formulate the psychophysiological signature of each subjective state with the required degree of precision, as demonstrated by inconsistent findings from many studies in this area (Cacioppo et al., 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 an emotional 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 the emotional signature itself (Stemmler et al., 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 that encompasses affective, motivational and cognitive dimensions of subjective experience as well as the psychophysiological response. This was the logic underlying the development of the