Postural Control as a Probe for Cognitive State: Exploiting Human Information Processing to Enhance Performance

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The battlefield of the future will require the warfighter to multitask in numerous ways, seriously taxing the cognitive and perceptual capabilities of even the most advanced warrior. A principal concern in developing a better understanding of how current and proposed computational technologies can supplement and augment human performance in this and other environments is determining when such assistance is required. This challenge can be parsed into 2 components: determining what set of measurements accurately reflects cognitive state, and identifying techniques for synthesizing this set of measurements into a single collective cognitive state variable. The primary thesis of this proposal is that automatic human behavioral responses serve as inherent probes for cognitive state. Further, the human perception-action system is uniquely designed to capture, process, integrate, and act on an extraordinarily diverse range of information freely available in the natural environment. Together, this system and the surrounding environment which acts on it—and on which the system acts—form a dynamic coupling. Under normal conditions these couplings remain intact. When stressed, these couplings become degraded. Based on this understanding, the

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authors propose a unique suite of Cognitive Workload Assessment (CWA) tools, based on real-time measurements of postural control that can serve as both a stand-alone indicator of cognitive state as well as a cueing filter for engaging other CWA sensor suites that are currently under development.

1. INTRODUCTION

Warfighters are increasingly engaging in a novel type of warfare, serving as active participants in battles while physically and geographically removed from the actual battle site. These warfighters are often seated while they engage in critical command and control activities or operate unmanned robotic vehicles through virtual interfaces. To optimize performance during these critical tasks, there is a need to (a) monitor their cognitive engagement (or immersion) in the virtual battlefield environment, (b) cue delivery of additional information to augment cognitive engagement, and (c) alert commanders for the need to relieve personnel when cognitive functions have degraded to the point where task performance is at risk. Current efforts addressing this challenge focus on (a) identifying objective measures from the neural and physiological domains, (b) correlating these measures to cognitive states, and (c) developing strategies for optimizing these states in synchrony with the warfighter’s needs (Schmorrow & Kruse, 2002a, 2002b).

This approach is not without its challenges. One critical issue in using such physiological measures as EEG or pupillometry is that they are highly susceptible to confounding factors. For example, EEG recordings are acutely susceptible to artifacts, including eye movement, blinking, and other noncerebral sources of activity (Cantor, 1999), as well as to other, less controllable factors, such as time between EEG recording and even food intake (Fishbein, Thatcher, & Cantor, 1990). Further, pupillary responses are modified in conjunction with vergence eye movements (Leigh & Zee, 1992), emotional states, or anticipated conditions (e.g., Bitsios, Szabadi, & Bradshaw, 2002; Loewenfeld, 1993; White & Depue, 1999). Hence, these measurement techniques require highly controlled environments and will require a significant investment in future developments, to provide a truly viable approach for measuring human performance under noncontrolled conditions. In the interim, alternative measures should be considered for use as both the core metrics as well as for validating other measures.

Toward this end, this work focuses on exploiting automatic motor behaviors to develop quantitative or semiquantitative metrics (or gauges) for cognitive engagement in seated warfighters. The primary thesis is that automatic human behavioral responses serve as inherent, unobtrusive, and noninvasive probes for cognitive state. Specifically, the authors assert that the human perception-action system is uniquely designed to capture, process, integrate, and act on an extraordinarily diverse range of information freely available in the natural environment (Gibson, 1966; Harris & Jenkin, 1998; Lee & Reddish, 1981; Warren & Whang, 1987). Together, this system and the surrounding environment which acts on it—and on which the system acts—form a dynamic coupling (Kelso, Delcolle, & Schoner, 1990; Schoner, Dijkstra, & Jeka, 1998). Under normal conditions, the couplings related to
automatic, coordinated behaviors, such as posture control, remain intact. When stressed, the complexity and coordination of these couplings degrade (Haken, Kelso, & Bunz, 1985; Kelso, 1995). Once correlated with changes in cognitive state—and the attendant decrease in task performance—the degradation of these automatic behaviors can then serve as an objective metric for determining when techniques for augmenting cognitive state should be applied to restore performance to acceptable levels.

The implications for this approach, namely, that dynamic couplings serve as a window into higher order perceptuo-cognitive-motor states that can cue automated performance enhancement tools, are far-reaching. Not only can the loop begin to be closed on human-computer interactions in a manner once considered to lie in the realm of fiction, but these dynamic interactions can also be identified and explored with the goal being to gain a more general understanding of how the human nervous system manipulates and responds to sensory information. Ultimately, these goals are to provide a deeper understanding of how the central nervous system processes, integrates, and acts on information available to it in the external environment, and to set the stage for developing and implementing a unique paradigm for using advanced human–computer interfaces to noninvasively exploit these relations to enhance performance.

2. BACKGROUND

Posture serves as an ideal system for identifying deeper cognitive states, because, from a basic neurophysiologic perspective, postural control is supported by essentially all sensory modalities. Vision (Lee & Lishman, 1975), proprioception (Jeka, Schoener, Dijkstra, Ribeiro, & Lackner, 1997), vestibular sensation (Day, Severac Cauquil, Bartolomei, Pastor, & Lyon, 1997), and even audition (Sakellari & Soames, 1996; Tanaka, Kojima, Takeda, Ino, & Ifukube, 2001), each provide a potential source of information for stabilizing an inherently unstable system (Peterka, 2002). Although input from these sources assists in the maintenance of stable posture, alterations in any of them lead to changes in overall system stability.

Hence, the postural system is, potentially, acutely susceptible to subtle changes. Observation has shown how visual immersion in an OmniMax theater elicits postural responses from an audience. Examples of such effects abound in the experimental literature. For example, simply rotating the visual surround or oscillating the base on which an individual is standing (Buchanan & Horak, 1999; Nardone, Cornà, & Schieppati, 1990) can destabilize posture, as evidenced by increased sway (Peterka, 2002). At the same time, it is becoming increasingly clear that the control flexibility evidenced by the posture stabilization system might actually serve as an adaptive response: although posture can be altered by changes in the surrounding sensory information, changes in posture can support “exploratory” behavior (Gibson 1966), through which the posture system actively probes the information (Riccio, 1993). For example, postural responses in the OmniMax theater may, in addition to serving as natural reactions to sensory input, provide sensory feedback information sufficient to discriminate between real and fictive self-motion.
The cognitive component provides yet another level of complexity to the system dynamics. To date, exploration of the role of cognitive workload on posture has focused only on the impact of simple cognitive tasks on stereotypical, upright posture. Recent work, capitalizing on different types of dual-task paradigms (Redfern, Muller, Jennings, & Furman, 2002; Shumway-Cook & Woollacott, 2000; Yardley et al., 2001), has begun to unearth this relation in greater detail. In general, these studies indicate that there are measurable trade-off relations between postural control and cognitive task demands. The open challenge, then, is to exploit these trade-off relations to unobtrusively assess cognitive state during task performance. Critical to this effort is developing novel measures of cognitive workload based on changes in posture.

3. DEVELOPMENT OF POSTURAL PROBE

3.1. Experiment Setup

To develop such measures—which could be termed postural probes—initial studies have been conducted on a prototype Dynamic Postural Assessment Chair (Figure 1). This prototype is an Operator’s chair from Lockheed-Martin’s Sea Shadow ship, which has been reupholstered with slip covers containing Ultrathin 16 × 16

FIGURE 1 Dynamic Postural Assessment Chair. The chair is a basic Operator’s chair from Lockheed-Martin’s Sea Shadow ship. Pressure sensor arrays are embedded within the upholstery (seat bottom and seat back). Head and trunk position are indicated through a Flock of Birds tracking system. One sensor is mounted on the participant’s head, a second one on the participant’s torso, and a third on the chair as a reference. The Warship Commander Task is presented on the LCD monitor located in front of the chair.
pressure sensor arrays (Vista Medical, force sensitive applications pressure mapping pads). Separate sensor arrays are used to measure the distribution of pressure on the seat bottom and the seat back at a rate of 4.5 Hz. A Flock of Birds (Ascension Technologies) tracker is used to monitor the position of the head and trunk (midsternum) with 6 degrees of freedom at 103 Hz. A stand supporting a 15-in. LCD monitor, a keyboard, and mouse pad was positioned in front of the participant for presentation of a military air defense simulation, the Warship Commander Task (WCT; St. John, Kobus, & Morrison, 2002).

This task presents a series of 75-sec trials with waves of friendly, hostile, and unidentified planes, which must be tracked, identified (using an “Identify Friend or Foe,” IFF, interrogation command), warned (if hostile and within the ship’s defensive perimeter), and, if necessary, neutralized. Workload is varied by modifications of (a) the number of planes in a wave (6, 12, 18, or 24), (b) the proportion of unidentified planes, and (c) a secondary auditory information processing task. The WCT software provides performance statistics, including second-by-second tracking of the number of planes on the screen and the number of tasks pending (e.g., IFF, warning and missile deployment). Posture-related data are collected on a PC using LabView (National Instruments) software and analyzed offline using routines written for MATLAB (MathWorks) and Excel (Microsoft). WCT task performance data are saved directly to Excel-compatible text files (St. John et al., 2002).

3.2. Results

Preliminary results suggest that the trade-off between posture and cognition can be captured through two measures. These examples of simple postural probes for cognitive workload during the WCT are termed (a) the monitor engagement head response, and (b) the back bracing response. The monitor engagement head response provides a global, long-term probe for cumulative engagement in continuous task. This response is a small magnitude (1–10 mm) head movement relative to the monitor during WCT waves (Figure 2) that follows a simple exponential time course (time constant: 20 sec). For first level of analysis, the head movement data can be decomposed into two components (Figure 3), the exponential response [constant + magnitude * exp(-t/20)] and the root mean square residual error (rms). Representative fits of the exponential response component to subject data are shown as solid lines in Figure 2. Note that the deviation of data from the exponential component (i.e., residual) is greater for the 18-track wave than for the 24-track wave. The magnitude divided by residual rms is proportionate to the number of tracks in the WCT wave.

Closer analysis, however, shows that this response template is produced by a tight relation between the magnitude of anterior–posterior head movement and the instantaneous number of targets on the monitor during the first half of a wave. As shown for waves of 6 and 24 tracks for one participant (Figure 4), head position initially parallels the increase in the number of targets, then remains fixed at a plateau until the conclusion of the wave. Figure 5 shows that the response is roughly a linear function of the number of targets for the first half of a wave. Thus, the monitor engagement head response is hypothesized to be a “sample-and-hold” detector
of cumulative task demand during a behaviorally relevant trial. A deficient response would indicate a lack of vigilance to the task.

The back bracing response, on the other hand, appears to be correlated with instantaneous changes in workload. The back bracing response is assessed by calculating the standard deviation of the rate of change in pressure (normalized to maximum pressure) over the 16 × 16 back sensor pad on a second-by-second basis. Preliminary analysis suggests that this metric shows values below 0.2 when participants are actively bracing themselves in the chair. Values above 0.2 are associated with instantaneous postural adjustments and indicate periods of low bracing. The periods of low bracing (Color Plate 8, Figure 6; red plus signs) appear to show a distinct distribution during the WCT sessions: they are associated preferentially with a few (or no) pending tasks or either static or decreasing numbers of pending tasks. In fact, there is approximately 80% probability that low back bracing detection will occur when the participant’s number of pending tasks in a trial block is either static or decreasing. This phenomenon is analogous to the phenomenon of drivers bracing themselves against the seat and steering wheel when traveling a winding road in heavy traffic, but relaxing when the road opens into a straightforward with extra lanes to decrease traffic density. This unobtrusive gauge indicates that WCT operators brace until they perceive an easing of the workload.
FIGURE 3 Global decomposition of the monitor engagement response (naso-occipital head movement data) into two components—Left = raw anterior–posterior head movement data; right = the raw head movement data are treated as a summation of the exponential-like response, summarized by a magnitude parameter (top) and noise (bottom), summarized as root mean square residual error. These two parameters, then, summarize performance during a Warship Commander Task wave. The magnitude parameter divided by the root mean square residual error serves as a global gauge of performance during the wave. A value of this tends to increase with the number of targets in a wave.

4. DISCUSSION

4.1. General Results

These initial studies indicate that different components of seated postural behavior can be used as unobtrusive gauges of cognitive engagement. One source of richness in these responses is the fact that these components operate on different time scales. These initial gauges serve as exemplars of two distinct temporal classes of cognitive assay: (a) “global or cumulative engagement detection” and (b) “instantaneous task demand detection.”

The monitor engagement response of the head is an example of a global or cumulative engagement detector. This very small translational head movement along the naso-occipital axis may be conceptualized as a “level detector” (tonic response or low-pass filter) of vigilance or attention allocation to a particular task. The response initially shows a relatively linear magnitude change with increasing workload (targets on the monitor in the WCT). A static deviation then
FIGURE 4  Relation between the monitor engagement response (naso-occipital head movement) and the number of targets on the screen during Warship Commander Task waves. The head position data (solid lines) are displayed in cm. The number of targets on the screen (dashed lines) have been normalized to the same magnitude as naso-occipital head position on the graphs, to illustrate the similarity in shape of the responses during the first 25 to 40 sec of a wave. This movement is followed by maintenance of head position at a fixed distance for the monitor, until the participant drops backward as the workload is completed.

persists until the task is completed to the satisfaction of the operator. As a result, it is sensitive to the cumulative workload or anticipated task demands during its buildup to the response plateau, but relatively insensitive to small fluctuations in workload during that period. Further, because the response during the WCT has a long-time constant (20 sec), robust identification of an appropriate buildup occurs within 10 sec to 20 sec. However, the rapid “release” of a fully developed response from its plateau (or “fully engaged”) position, as seen at the end of each WCT wave (Figures 2 and 4), may be a sensitive temporal indicator of contexts such as (a) appropriate task completion, (b) a shift of attention or vigilance, or (c) a loss of vigilance.

The back bracing response is an example of a gauge that appears to be sensitive to instantaneous processing demands. It is conceptualized as a detector of changes (phasic response or high-pass filter) in immediate workload. In this sense, it is the converse of the monitor engagement response because it is associated with changes in workload, independent of the current workload level. A low gauge value (or “constant” pattern of back pressure) can appear across all workload contexts. However, a high gauge value (i.e., a postural adjustment) occurs preferentially (but not obligatorily) when workload (defined as tasks pending for the operator) is constant or decreasing. These relations are shown in Color Plate 8, Figure 6 (lower panel) for a series of 12 waves of the WCT (three repetitions of waves of 6, 18, 12, and 24 tracks). The
FIGURE 5  Linear relation between naso-occipital head movement and the number of targets on the screen during the first 38 sec of Warship Commander Task waves. The data from the initial 38 sec of the responses in Figure 4 have been replotted with time as an implicit variable. The linear relation suggests that the exponential rise of the monitor engagement response is produced by a small head movement (relative to the monitor) that is proportional to the instantaneous number of targets on the screen.

gauge values have been truncated on the graph to a maximum value of 0.8 for display purposes and were binned for analysis on a second-by-second basis. Note that the high values (> 0.2) of the gauge in this representative participant had an 80.5% likelihood of coinciding with a constant or decreasing workload.

One can, therefore, formulate the following conceptual framework. There is a trade-off between the need to brace one’s posture for WCT performance and the need to adjust one’s posture (for comfort or any other purpose). In the experimental sessions, a fixed posture (low gauge value) may occur at any workload, as an indicator of a trade-off toward WCT engagement. On the other hand, a constant or decreasing workload is associated with an increased probability of initiating postural adjustments, which are contextually appropriate in an engaged or immersed participant. Stated simply, the postural adjustment is being deferred until the workload is “under control.” Postural adjustments during a period of increasing instantaneous workload occur with less frequency, likely representing a benign trade-off (in this experimental paradigm) of an interruption (momentary postural adjustment or fidgeting) versus task performance.

4.2. Applications

The results of these initial studies with the WCT should be regarded as an initial proof-of-concept that seated postural behaviors can serve as probes for cognitive
state. The Dynamic Postural Assessment Chair has been used to derive two quantitative gauges associated with task demands for a computer operator engaged in a simple, simulated air defense task. As is the case in any initial demonstration of an approach or technology, one must acknowledge that it is unknown whether the algorithms for response detection will generalize to other tasks. However, it is important to note that these test conditions were relatively undemanding for postural control: The participants were seated on a static platform at a keyboard, mouse, and monitor. Although this approach may be useful for monitoring cognitive engagement in analogous environments (e.g., air or rail traffic controllers), the potential sensitivity of this approach is far greater when the test bed is a moving platform, such as a ship, helicopter, or land vehicle. In particular, monitoring the trade-offs between (a) machine dictated postural demands (e.g., monitor engagement and back bracing responses in the vehicle’s spatial frame of reference), and (b) postural control demands (e.g., vestibular reflex sensitivity in the earth and inertial frame of reference) can reasonably be expected to enrich the ability to unobtrusively probe cognitive states in a range of seated environments.

Consider the range of applications this technology presents the civilian and military sectors. For example, as the Navy and merchant marine push the envelope by reducing manning aboard ships, many of the systems once monitored by crew members will come under the control of next-generation computer systems. These systems, in turn, will be monitored by only a handful of (seated) crew members. This decrease in available human resources imposes a significant human–computer interface challenge on ship designers: There will be a need to present large quantities of information, continuously, in a meaningful fashion to a limited crew. This scenario is potentially vulnerable to loss of situational awareness through overloading of cognitive capabilities. The manpower reduction goals will impact analogously on the design of operator-machine interfaces for land vehicles (e.g., trains, long-haul trucks, and cars) and both rotor and fixed-wing aircraft for both civilian and military applications. Thus, maximizing the efficiency of human–computer interfaces—especially in terms of ensuring that the designated crew member is continuously operating within peak cognitive performance—becomes a critical and technology-limiting concern.

The current technology provides a first-level filter for quickly and unobtrusively detecting when significant changes in user state are not only occurring, but are pending. Hence, these results suggest a technique for ensuring that corrective measures can be executed in advance of an actual decrement on task performance. A second application for this technology is in the use of Unmanned Aerial Vehicles (UAVs). Within all branches of the armed forces, these devices are quickly becoming an integral part of the military commander’s mobile arsenal. Currently, each UAV requires a significant investment in (human) support to execute its mission. As with the Navy’s push toward reduced manning aboard ships, efforts are currently underway to reduce the number of humans required to operate these UAVs by automating much of the basic routines involved in flying these devices. This trend will inevitably require fewer human operators to process significantly larger quantities of information, over shorter time scales. As in the case of naval platforms, these operators will run the risk of becoming overloaded cognitively. The current technology could be integrated into the operators’ chairs to either predict
impending overloading in an operator or to identify those operators in whom this overloading has already occurred.

The current technology also presents a wide range of commercial applications for environments within which key individuals are seated. For example, driver vigilance is an area that has received widespread attention, especially among long-haul truck drivers. One strategy is to use continuous video monitoring of eye movements to detect changes in patterns of eyelid closure (Grace et al., 1998) or eye movement dynamics. However, Rogé, Pebayle, and Muzet (2001) demonstrated that participants in a simulated automobile driving task made many postural adjustments during periods of low vigilance, which corresponds to common anecdotal experiences with long-distance driving. Our back bracing gauge, and an analogous seat bracing gauge, can objectively detect such adjustments. Hence, integration of our sensor suite into the very fabric of the drivers’ seat has the potential to detect unobtrusively periods of reduced driver vigilance.

REFERENCES


