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Electrophysiological, behavioral, and subjective indexes of workload when performing multiple tasks: manipulations of task difficulty and training

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Abstract

This study examined whether alpha event-related desynchronization (ERD) and theta event-related synchronization (ERS) could successfully measure changes in cognitive workload and training while an operator was engaged in a continuous, interactive, control task(s). Alpha 1 (8–10 Hz) ERD, alpha 2 (10–12 Hz) ERD, and theta (3–7 Hz) ERS were determined for a communications event that occurred during multiple task workload conditions or as a single task. Other measures (alpha and theta EEG power, heart rate, respiration, eye blinks, behavioral performance, and subjective workload ratings) were also evaluated. Results showed that alpha 2 EEG, heart rate, behavioral, and subjective measures were sensitive to changes in workload in the multiple tasks. In addition, eye blink rate and behavioral measures were sensitive to training. Alpha ERD and theta ERS were not sensitive to workload and training in our interactive, multiple task environment. However, they were effective indexes of cognitive/behavioral demands within an interactive single task.

Keywords: EEG; ERD; ERS; ECG; Alpha; Work load; Theta; Training

1. Introduction

The present study examines the utility of measuring variations in synchronized brain electrophysiological activity to infer changes associated with mental workload during multiple task performance. The advantage of using brain event-related activity to infer workload is that it provides good temporal resolution of cognitive activity. In contrast, peripheral psychophysiological measures (i.e. heart rate, respiration and eye blinks) are imprecise regarding the temporal resolution of

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cognitive activity. Furthermore, behavioral measures, as well as subjective measures, are not always reliable indexes of workload (e.g. Yeh and Wickens, 1988). Thus, sensitivity of brain event-related changes to differing levels of workload are of special interest.

Numerous studies have shown that cognitive processing results in attenuation of the alpha brain electrical rhythm (e.g. Berger, 1969; Glass, 1966; Gundel and Wilson, 1992) and enhancement of theta activity (e.g. Rugg and Dickens, 1982; Mecklinger et al., 1992). We were specifically interested in the influence of task variables on the phasic attenuation or desynchronization of alpha power and phasic increase of theta power during multiple task performance relative to a time-locked reference interval. This can be measured by event-related desynchronization (ERD) of the alpha rhythm or event-related synchronization (ERS) of theta activity as quantified by Pfurtscheller and Aranibar (1977); Pfurtscheller and Klimesch (1991) and Klimesch et al. (1994). In addition to its temporal resolution, alpha ERD (Pfurtscheller, 1988) and theta ERS (Klimesch et al., 1994) can have a specific spatial representation. For example, single-task studies have shown that alpha ERD is maximal at occipital sites during visuospatial tasks (e.g. Pfurtscheller and Aranibar, 1977), maximal over temporal sites during auditory discrimination tasks (e.g. Kaufman et al., 1991), and is maximal at centro-parietal sites when movement is required (e.g. Pfurtscheller and Aranibar, 1979). Also, localized frontal increases in theta band ERS have been found in tasks involving episodic memory (Klimesch et al., 1994) and to words that were successfully encoded or retrieved (Klimesch et al., 1997). Thus, alpha ERD and theta ERS can be used to investigate cortical activation patterns in space and time (e.g. Pfurtscheller et al., 1988; Klimesch et al., 1990; Pfurtscheller, 1991).

Task difficulty in single-task paradigms has been shown to increase alpha ERD amplitude and duration. For example, van Winsum et al. (1984) showed increased alpha ERD amplitude and duration at central–parietal and central–occipital sites in a target detection task that required subjects to detect the presence of one of four possible targets (difficult task) compared to only one target (easy task). Boiten et al. (1992) showed increased alpha ERD and duration in right parietal sites in a same–different task when same–different judgments were based on words (difficult task) as opposed to letters (easy task). These latter increases in alpha ERD were found even though increased task demands (i.e. speeded instructions) were shown to decrease alpha power in the prestimulus reference interval. Also, Dujardin et al. (1995) showed increased alpha ERD amplitude and duration that was more widespread in a difficult visuo-spatial task relative to an easier verbal task.

Although the effects of task difficulty upon theta ERS have not been investigated, there is a literature showing increased theta band power in tasks with higher mental demands. Thus, it is expected that theta ERS activity would also increase in high mental workload situations. For example, Rugg and Dickens (1982) found increased parietal theta activity in their more difficult visuospatial task than in their easier verbal task. Gundel and Wilson (1992) found increased left frontal theta to be associated with increased memory load. Additionally, Laukka et al. (1995) reported increased frontal theta during the more difficult segments of a simulated driving task.

One purpose of this study was to determine whether alpha ERD and theta ERS could successfully measure workload of a complex, single event while a subject was engaged in multiple, interactive tasks. To date only behaviorally simple, single-task paradigms have been used to demonstrate alpha ERD and theta ERS effects (e.g. van Winsum et al., 1984; Geuze and van Winsum, 1987; Kaufman et al., 1991; Pfurtscheller et al., 1992, 1994; Derambure et al., 1993; Klimesch et al., 1994). Of additional interest was whether alpha ERD and theta ERS could be used to discriminate novice from experienced operators. In the present study a communication task was common to four workload conditions from which alpha ERD and theta ERS were derived.

Two different alpha bands 8–10 Hz (alpha 1) and 10–12 Hz (alpha 2) as well as the 3–7-Hz theta band were examined. Alpha 1 ERD is *usually* more topographically widespread and may represent attentional and motivational processes related to alertness and the allocation of limited processing resources. In contrast, alpha 2 ERD has been shown to be more localized and may reflect processes that are directly stimulus-related which include sensory-motor processing and possibly semantic encoding (see Pfurtscheller, 1988; Klimesch et al., 1992, 1996; Krause et al., 1994). In line with previous research, both alpha 1 and alpha 2 ERD amplitude is expected to increase with increases in task demands or workload. In addition, because training should reduce workload demands, alpha 1 and 2 ERD amplitude is expected to decrease with training. Duration of alpha ERD could not be evaluated due to the continuous, interactive nature of our tasks. While no studies have investigated the effects of differing levels of mental workload on theta ERS, it is expected that theta ERS will increase with increased mental demands and decrease with training as learning should reduce mental demands.

Additionally, other physiological, behavioral and subjective measures were recorded in order to provide converging operations to index workload and training. These other measures included: (1) alpha and theta electroencephalogram power spectra; (2) cardiac activity, respiration, and eye blinks; (3) behavioral measures of reaction time (RT) and accuracy; and (4) subjective ratings of task difficulty (for a review of these measures, see Eggemeier and Wilson, 1991; Kramer, 1991; Wilson and Eggemeier, 1991).

2. Methods

2.1. Subjects

Four males and six females aged 18–26 participated as paid volunteers. All were right-handed and had normal or corrected-to-normal vision. The data from one male were excluded due to extremely poor task performance.

2.2. Electrophysiological recording

2.2.1. Electroencephalogram (EEG)

Neuroscan software, amplifiers, and an Electro-Cap were used to record EEG from 58 active scalp sites referenced to linked mastoids. Calibration was done at 500 μV at 10 Hz and showed an error range of 0.707 μV RMS. Data were digitally filtered at 0.1–30 Hz (-6-dB gain, ≥ -12-dB octave slope) and amplified (gain 1000, resolution 084 μV/Bit, range 5 μV) via Synamps (5083) amplifiers, sampled at 200 Hz and stored off-line for analysis. Task event markers were recorded at the onset of each communication task.

Electrode positions were measured from seven of the nine subjects using the Polhemus 3D-Space system (Wang et al., 1994). These coordinates established the weighting factors for the nearest neighboring electrodes when computing reference-free surface Laplacian derivations. Because the variance of the electrode positions among subjects was extremely low, average values were used for the other two subjects.

2.2.2. Electrocardiograph (ECG), electrooculogram (EOG) and respiration

ECG was recorded using Ag/AgCl electrodes at the sternum and fifth intercostal space of the left ribcage with the ground electrode located above the fifth intercostal space of the right ribcage (impedences < 30 KΩ, Grass P511 amplifiers, filtered 10–100 Hz). Ag/AgCl electrodes positioned above and below the left eye monitored eye blinks and electrodes positioned at the outer canthus of each eye monitored horizontal eye movements (impedences < 10 KΩ, Grass P511 amplifiers, filtered 0.1–30 Hz). Respiration was recorded using a Respitrace system with elastic transducer bands on the chest and abdomen. Respiration amplitudes were individually calibrated immediately prior to data collection. Activity was sampled at 1000 Hz.

2.3. Task apparatus and stimuli

Subjects were seated at a table in a sound attenuated, electrically shielded chamber. Subjects controlled a joystick with their right hand and a computer mouse with their left hand. Visual displays were presented on a monitor centered 38 inches from the subject. Computer generated audio messages were presented over a speaker centered in front of the subject. Subjects were presented with four tasks, using the Multi-Attribute Task Battery (MATB; Comstock and Arnegard, 1992). Fig. 1 shows the MATB visual displays.

2.3.1. Light detection task

Subjects were to detect the offset of a green light (F5) and the onset of a red light (F6). The boxes subtended approximately 1.2° of visual angle. Subjects indicated detection by moving a cursor to the box and clicking the mouse. This caused the lights to return to their original state.

2.3.2. Gauge monitoring

Subjects monitored four different gauges (F1, F2, F3 and F4), each subtending 2.4° visual angle, and determined whether a yellow pointer fluctuated more than one unit above or below the center line. Subjects indicated detection by moving the cursor to the faulty gauge and clicking the mouse. Afterwards, a yellow bar (0.12° visual angle) appeared at the bottom of the gauge, and the fault was corrected.

2.3.3. Tracking

The goal of this task was to keep a green circle (0.6° visual angle), in a center rectangular area (1.8° visual angle) by moving the joystick (first order control) (see center panel in Fig. 1). The disturbance function for tracking consisted of a sum of non-harmonic sine waves. The frequency of the disturbance function varied for low, medium, and high tracking according to the MATB program specifications.

2.3.4. Communication

Audio messages were 6 s in duration and consisted of a six-digit call sign followed by a command. Alpha ERD and theta ERS were derived from this event only. The same target call sign was used for each subject and any other call sign was irrelevant and to be ignored. The command indicated which of four channels (lower left in Fig. 1) needed its frequency adjusted. A channel was selected by clicking the mouse on the channel name (e.g. NAV1). The frequency was changed by positioning the cursor and clicking the mouse on

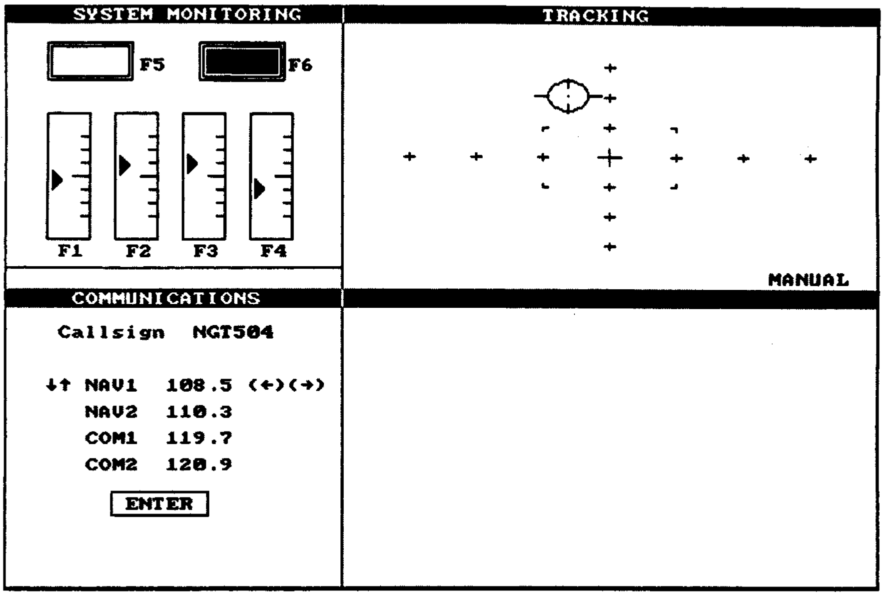

Fig. 1. Multiple Attribute Task Battery screen (MATB). The light detection and gauge monitoring stimuli are located in the upper left corner. The tracking task cursor and home position are shown in the center. The communication task response area is in the lower left corner.

the arrow icons (see Fig. 1). After the frequency changes were made, the cursor was clicked on the 'Enter' box (1.2° visual angle) causing the borders to brighten. Text characters (channel name, frequency and arrows) measured 0.36° visual angle.

2.3.5. Workload ratings

The NASA Task Load Index (TLX) (Hart and Staveland, 1988) was used to obtain a self reported assessment of workload during the multi-task conditions. Subjects rated their exertion from low (1) to high (10) in the following six subscales: Mental demand, physical demand, performance, temporal demand, effort, and frustration.

2.4. Procedure

2.4.1. Practice

At the beginning of the experiment, subjects practiced controlling the mouse with their left hand for approximately 9 min.

2.4.2. Experimental sessions

The trial length for each condition was 3 min.

The *single task* condition required monitoring of the communication task only. There were eight target communication events and two noise events each separated by at least 7 s.

The *multi-task* conditions required monitoring of all tasks. All of the multi-task conditions contained 10 communication events (eight target, two noise) each separated by at least 7 s. The *multi-task low* condition contained four light detection events, four gauge faults, and a low difficulty tracking disturbance. Onset of each of these events were separated by at least 9 s. The *multi-task medium* condition contained 12 light detection events, 10 gauge faults, and a medium difficulty tracking disturbance. Onset of each of these events were separated by at least 3 s. The *multi-task high* condition contained 16 light detection events, 18 gauge faults, and a high difficulty disturbance function for tracking. Onset of each of these events were separated by at least 2 s.

Subjects were instructed to treat tracking as the primary task, the communication as the secondary task, and to time share these tasks with the light detection and gauge monitoring tasks. All tasks were to be performed as quickly and accurately as possible. Accuracy (false alarms and misses), RTs, and tracking root mean square (RMS) were recorded. A miss was recorded if subjects did not respond to any target within 15 s.

Subjects completed six sessions. In sessions 1 and 6, electrophysiological, behavioral, and subjective data were collected. Subjects completed 24 trials (six trials each of the four conditions). Subjects completed the subjective workload rating after the last trial of each of the multi-task conditions. Sessions 2–5 were training sessions during which only behavioral data from 10 trials in each multi-task condition were recorded. The order of task conditions in each session was random with the constraint that no two of the same conditions occurred in sequence. Sessions 1 and 6 required approximately 3 h (including 60 min for instrumentation). Sessions 2–5 required 90–110 min. Subjects rested 1–2 min after each trial and 10–15 min midway through each session.

2.5. Data analysis

2.5.1. ERD and ERS

The eight relevant communications task epochs were identified within each trial. Alpha ERD and theta ERS were derived from onset of the eight relevant communication stimuli. Epochs (10-s) (2-s prestimulus and 8-s post-stimulus) were submitted to an instantaneous frequency analysis in the alpha 1 (8–10 Hz), alpha 2 (10–12 Hz) and theta (3–7 Hz) frequency bands. The amplitude values (5-ms resolution) were averaged over 25 consecutive data points in order to decrease variance. These were then squared, yielding an absolute power within each band every 125 ms. Because no windowing was applied, the first and last two data values in each epoch were eliminated. Thus, a total of 72 data points representing a 9-s period (1.5-s prestimulus, 7.5-s post-stimulus onset) were generated. Individual trial data were log transformed to correct for skewness. To derive the ERD and ERS, the average of the communication prestimulus period was subtracted from each communication post-stimulus data point for each trial. Averaged alpha 1 ERD, alpha 2 ERD, and theta ERS was then computed for each subject, site, session, and workload condition (24 epochs per condition).

2.5.2. FFTs

An average Fast Fourier Transform was calculated for each 3-min trial at each electrode site. Each trial was sorted into 512-ms epochs and averaged in the frequency domain using a Parzens window yielding FFTs with a resolution of 0.39 Hz. The FFTs were then grouped into three bands: alpha 1 (8.2–10.1 Hz), alpha 2 (10.5–12.8 Hz), and theta (3.1–7.8 Hz). Data were log transformed and the relative powers were calculated.

2.5.3. EEG analysis

Continuous EEG data were corrected for vertical and horizontal eye-movement artifacts using the NeuroScan correction procedure (Semlitsch et al., 1986). The data were then transformed using the local finite-difference approximation (Hjorth, 1980) based upon inter-electrode distances. Equipment failure resulted in the loss of scalp site T4L and the loss of two trials (subject 1, day 1, multi-task low and subject 4, day 2, single task). In seven other trials from two different subjects, data from specific sites were discarded due to movement and muscle artifacts.

2.5.4. ECG, EOG and respiration

For the ECG, the interbeat intervals (IBIs) between successive R waves were determined and outliers were corrected (Mulder, 1992). To assess heart rate variability (HRV), the inter-beat intervals were processed through a Porges–Bohrer filter (Delta-Biometrics Inc.) at settings corresponding to the medium (0.06–0.14 Hz) and high (0.15–0.40 Hz) bands. Respiration rates and amplitudes, as well as eye blink rates, amplitudes, and durations were similarly identified, and an average value for each 3-min trial was determined.

2.5.5. Statistics

All analyzes were based on a two-way within subjects analysis of variance (ANOVA) with the factors of workload condition (single task, multi-task low, multi-task medium, and multi-task high) and session (session 1 and 6). To evaluate the ERD, ERS, and FFT results, a Geisser–Greenhouse correction for sphericity was conducted at each electrode site for each bandwidth. The Tukey HSD was used for post-hoc comparisons ($P < 0.05$). Differences in regional EEG activity were considered to be significant over particular scalp regions if *five* or more nearby electrodes showed significant changes in EEG activity.

3. Results

A summary of significant results for each of the different measures is provided in Table 1.

3.1. Behavioral data

3.1.1. Multi-tasks

A composite Z-score was used to evaluate behavioral responses in the multi-task conditions. Behavioral responses were standardized within each subject by dividing RTs for each task by the proportion of correct responses and weighting each task measure by one-quarter and summing them together (Fig. 2a). There were main effects of workload ($F_{1,16} = 75.03$, $P < 0.0001$), and session ($F_{1,8} = 225.08$, $P < 0.0001$), and a Workload $\times$ Session interaction ($F_{2,16} = 14.02$, $P < 0.01$). Performance in both sessions 1 and 6 was worse in the multi-task high, intermediate in the multi-task medium, and best in the multi-task low condition ($P < 0.05$). In addition, performance was better in session 6 than in session 1. Furthermore, performance improved more in the high multi-task condition across sessions relative to the low and medium multi-task conditions ($P < 0.05$). These results show that performance decreased as workload increased and performance improved with training, especially in the high workload conditions.

3.1.2. Communication task

Three different responses were required to complete the communications task. For simplicity, only the final behavioral responses to the enter key selection is reported, even though EEG was

Table 1
Summary of significant results for each of the different measures

Measure	Workload tasks				Session	Condition × session
	Single vs. multi-task	Multi-low vs. med	Multi-low vs. high	Multi-med vs. high		
(1) Behavioral						
Multi-task	n/c	X	X	X	X	X
Communication	X	X	X	X	X	
(2) ERD/ERS						
Alpha 1 ERD	X					
Alpha 2 ERD	X					
Theta ERS	X					
(3) FFT						
Alpha 1	X					
Alpha 2	X		X			
Theta	X					
(4) Cardiovascular						
HR	X		X	X		
HR med. var	X		X			
HR high var	X					
(5) Respiration						
Amplitude						
Rate	X					
(6) Eye blink						
Rate	X				X	
Duration	X					
Amplitude	X					
(7) Subjective	n/c	X	X			

Abbreviations. X, significant difference, $P < 0.05$; n/c, not calculated; and var, variability.

recorded throughout the entire trial. There was a main effect of workload ($F_{3,24} = 16.24$, $P < 0.001$) and session ($F_{1,8} = 56.67$, $P < 0.001$) for correct RT. There was also a main effect of session for percent errors, miss and false alarms combined ($F_{1,8} = 8.39$, $P < 0.02$). As shown in Fig. 2b, RT was fastest for the single task, and became slower for the multi-task conditions as task difficulty increased ($P < 0.05$). This RT trend was observed in both sessions 1 and 6. In addition, for all tasks, RT was faster and miss errors were less frequent in session 6 relative to session 1. Thus, performance decreased as workload increased and improved with training.

3.2. ERD and ERS

Inconsistent with expectations, there were no significant differences in alpha 1 ERD, alpha 2 ERD or theta ERS between sessions or among the multi-task workload conditions ($P > 0.05$). However, there was a significant difference in alpha 1 ERD, alpha 2 ERD, and theta ERS between the single and multi-task conditions ($P < 0.05$). Furthermore, alpha 1 and 2 ERD and theta ERS, relative to the prestimulus baseline, was found among multiple electrodes in the single-task condition.

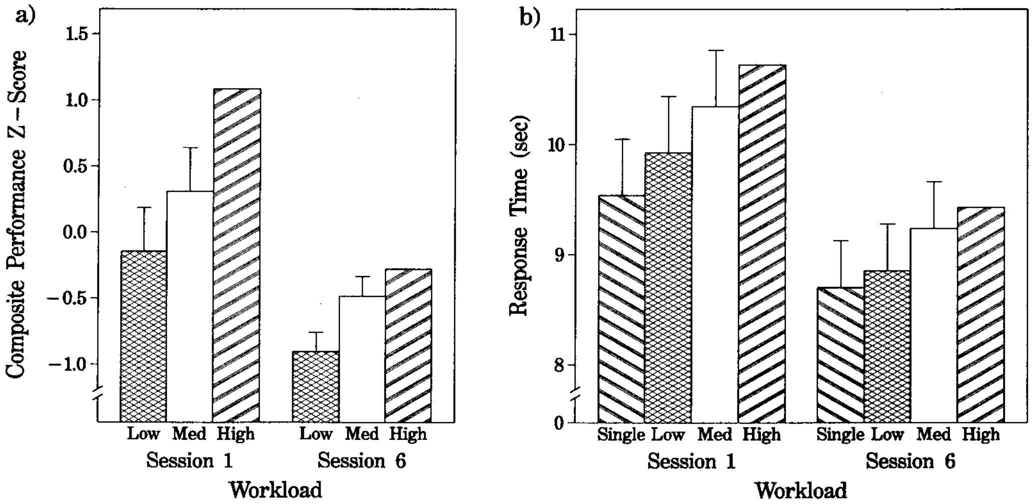

Fig. 2. Panel (a) shows the composite performance Z scores for the three multi-task workload conditions (low, medium and high) in each of the two testing sessions (sessions 1 and 6). Panel (b) shows the response times to enter the selected frequency for the communications task during each of the four workload conditions in each of the two testing sessions (sessions 1 and 6). Error bars represent Tukey's HSD values.

3.3. Single-task ERD and ERS

Figs. 3–5 represent the time course for the electrode sites that showed significant alpha 1 ERD, alpha 2 ERD and theta ERS, respectively, in the single task. Because there was no significant activity during the first 3 s of the communication event, the maps are shown beginning 3 s after auditory message onset and ending 0.5 s after the end of the auditory message.

3.3.1. Alpha 1

Significant ERD was found in the single task as

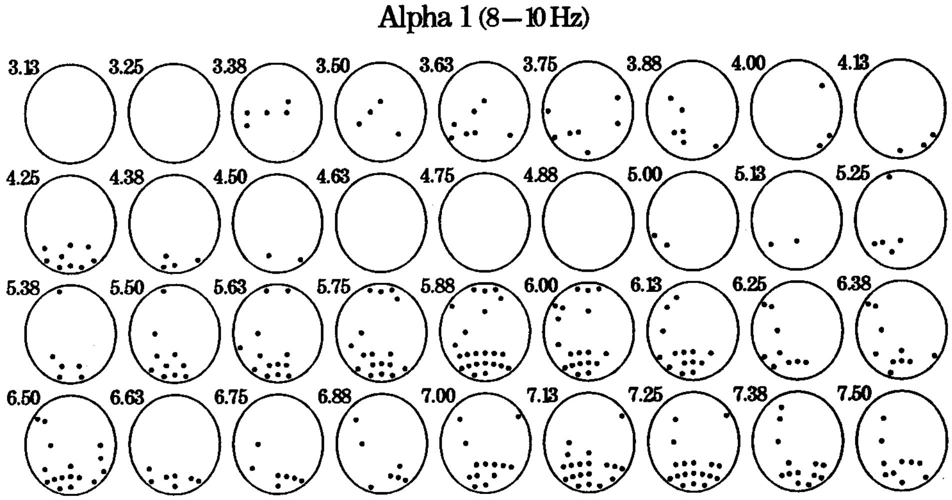

Fig. 3. Alpha 1 ERD for the single-task condition beginning 3.13 s after the start of the communication message and ending 0.50 s after the communication event terminated. Each circle represents the head at 0.125 intervals, with the front of the head facing upward. Each dot represents the position of an electrode site with a significant alpha 1 ERD ($P < 0.05$).

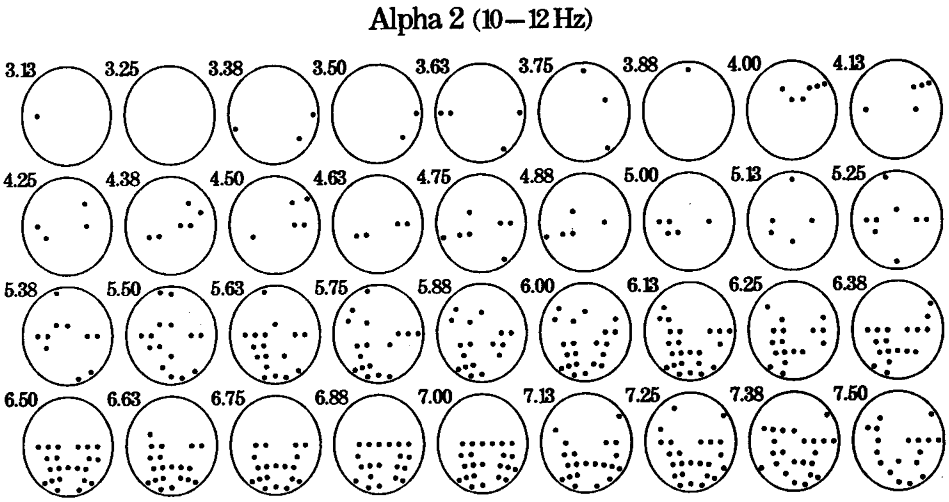

Fig. 4. Alpha 2 ERD for the single-task condition beginning 3.13 s after the start of the communication message and ending 0.50 s after the communication event terminated. Each circle represents the head at 0.125 intervals, with the front of the head facing upward. Each dot represents the position of an electrode site with a significant alpha 2 ERD ($P < 0.05$).

early as 3.38 s (middle of second call sign) at the left central sites, followed by significant activity at parietal and occipital sites (Fig. 3). This latter ERD activity dissipated, and occurred again around 5.25 s (after dial selection instructions, but before frequency setting instructions) mainly at parietal and occipital sites, especially in the left hemisphere. ERD differences continued at the parietal and occipital sites from the 5.25-s time point until at least 0.5 s after the message terminated. Note also that frontal ERD, as well as parietal and occipital ERD, occurred between the 5.75- and 6.50-s time points (during frequency setting instructions).

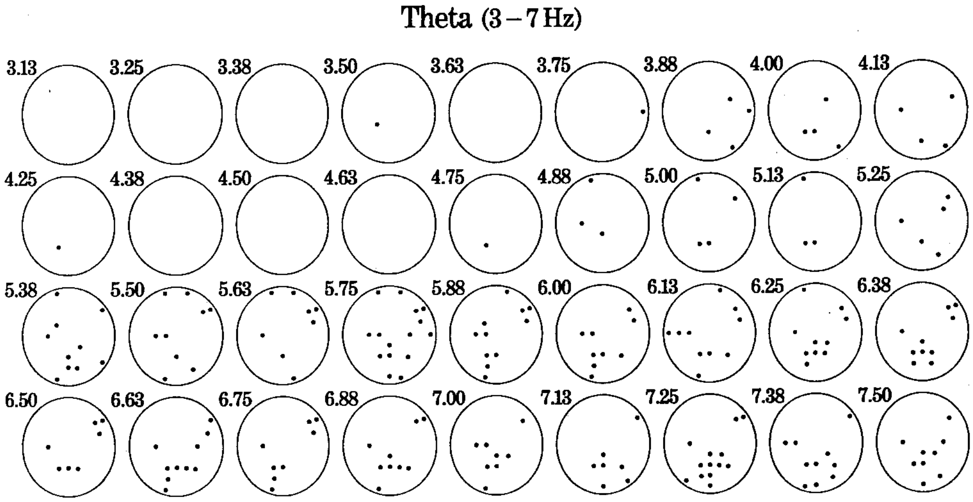

Fig. 5. Theta ERS for the single-task condition beginning 3.13 s after the start of the communication message and ending 0.50 s after the communication event terminated. Each circle represents the head at 0.125 intervals, with the front of the head facing upward. Each dot represents the position of an electrode site with a significant theta ERS ($P < 0.05$).

3.3.2. Alpha 2

Fig. 4 shows that significant ERD in the single task began 4.0 s after the start of the command message (during dial setting instructions, but before frequency setting instructions) in the right frontal–temporal and central sites. By approximately 5.50 s (after dial setting instructions, but before frequency setting instructions) the number of sites indicating significant ERD became wide spread at central, parietal and occipital sites (and activity sometimes occurred at left temporal sites) and continued at least 0.5 s after the message terminated.

3.3.3. Theta

Significant theta ERS began as early as 5.38 s at some parietal, central and right frontal sites (Fig. 5). Throughout the message and for 0.5 s after the message, the number of sites showing significant theta ERS was consistent at the parietal sites.

3.4. Multi-task ERD

The lack of significant ERD for the multi-task conditions may be due to a floor effect. ERD was calculated relative to the prestimulus baseline, and alpha 1 and 2 prestimulus baseline power was significantly less in the multi-task conditions relative to the single task at several electrode sites. Alpha 1 showed decreased power mainly in parietal and in some central sites ($P < 0.05$). Also, alpha 2 showed decreased power in the multi-task conditions in central, parietal, and occipital sites ($P < 0.05$). Further evidence that ERD was masked due to reduced prestimulus baseline power is illustrated in Fig. 6. This shows alpha 2 ERD from one electrode site (C3p) for the single-task and the multi-task medium conditions. The multi-task prestimulus baseline was greatly reduced and was equivalent to the ERD in the single-task condition. Further reduction following stimulus presentation was small or not possible. In contrast, the lack of intervening task activity during the single task resulted in a higher alpha power baseline permitting alpha reduction (ERD) during single-task performance.

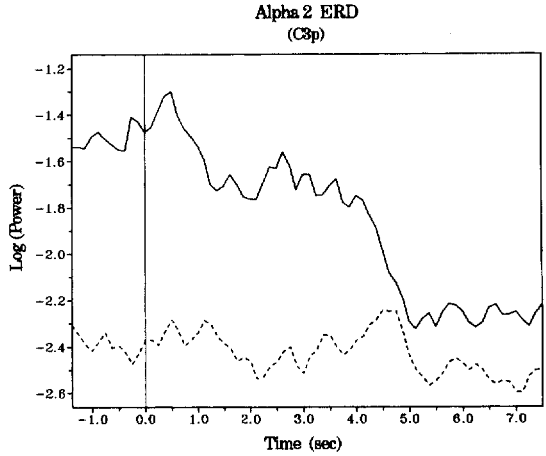

Fig. 6. Alpha 2 power for one subject from the C3p electrode site from the single task (solid) and multi-task medium workload conditions (dashed). The prestimulus baselines for the communication event are to the left of the vertical line at time 0.0. Alpha 2 power during the communication event is to the right of the vertical line. The graph shows the reduced alpha 2 power baseline and event related activity for the multi-task medium relative to the single task workload condition.

3.5. Alpha FFT

Relative power in the alpha 1 and alpha 2 FFT bands decreased at multiple sites during multi-task performance compared to the single task across the 3-min trial. Fig. 7a,b show the significant changes for the multi-task high relative to the single-task condition for alpha 1 and alpha 2, respectively. Alpha 1 power decreased over left occipital sites; while alpha 2 power decreased at mid-line occipital, right occipital, mid-line parietal, mid-line central, and left central sites. In addition alpha 2 showed some increased power at frontal sites.

Also, Fig. 7c shows that alpha 2, but not alpha 1, was affected by workload in the multi-task conditions. Alpha 2 power decreased at right central and parietal sites for the multi-task high relative to the multi-task low workload condition. Alpha 1 or alpha 2 were not different between the two recording sessions.

3.6. Theta FFT

The theta band FFTs showed significant in-

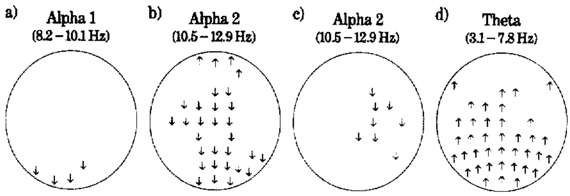

Fig. 7. Significant changes in the relative power (FFT) of alpha 1, alpha 2, and theta across the 3-min task interval. Each circle represents the head with the front facing upward. The arrows represent electrode sites showing significant power differences ($P < 0.05$) between workload conditions with the upward pointing arrows showing increased activity and the downward pointing arrows showing decreased activity. Panels (a) and (b) show differences between the multi- and single-task conditions for alpha 1 and alpha 2, respectively. Panel (c) shows alpha 2 differences between the multi-task high and multi-task low workload conditions. Panel (d) shows theta differences between the multi- and single-task conditions.

creases in relative power at multiple sites during the multi-task high condition relative to the single-task condition (Fig. 7d). The increased theta activity was wide spread over central, parietal and occipital sites with a tendency towards left central sites but with bilateral parietal and occipital involvement. There were, however, no significant differences between the two recording sessions or between the different levels of the multi-task conditions.

3.7. Peripheral physiological data

3.7.1. ECG

There was a significant main effect of workload for HR ($F_{3,24} = 21.87$, $P < 0.001$) as well as HRV in both the medium ($F_{3,24} = 13.12$, $P < 0.001$) and high bands ($F_{3,24} = 10.79$, $P < 0.001$). As shown in Fig. 8a, HR was significantly higher in the multi-task conditions relative to the single task ($P < 0.05$). Also, HR was significantly higher in the multi-task high condition relative to the multi-task low and medium conditions ($P < 0.05$). However, there was no significant difference between multi-task low and medium conditions. HRV in both the high and medium bands (Fig. 8b,c, respectively) was significantly less in all of the multi-task conditions relative to the single task. Also, HRV for the medium band was significantly reduced in the high relative to the low multi-task condition ($P < 0.05$).

3.7.2. Respiration

Although there were no significant effects for respiration amplitude, respiration rate showed a significant effect of workload ($F_{3,24} = 10.24$, $P < 0.001$). Fig. 9 shows that respiration rate was significantly faster during each of the multi-task

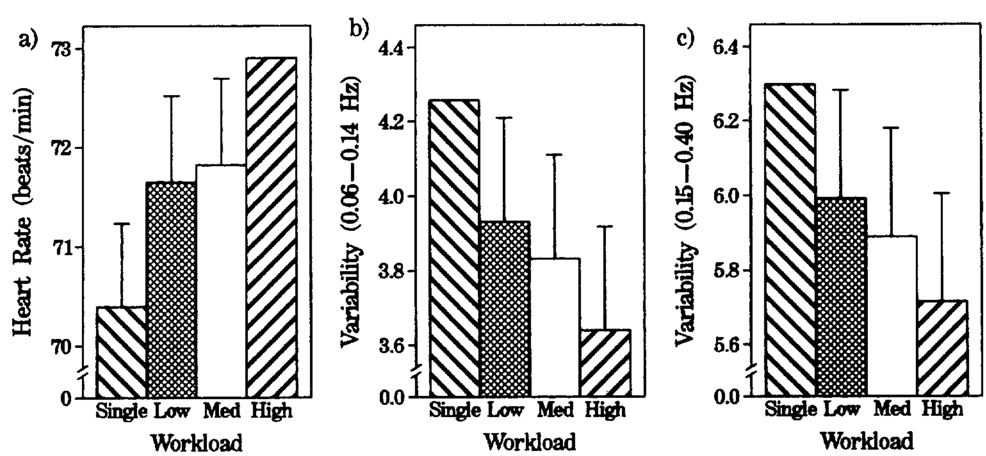

Fig. 8. ECG data during each of the four workload conditions collapsed over the two testing sessions (session 1 and 6): Panel (a) shows mean heart rate; Panel (b) shows heart rate variability in the medium band; and Panel (c) shows heart rate variability in the high band. Error bars represent Tukey's HSD values.

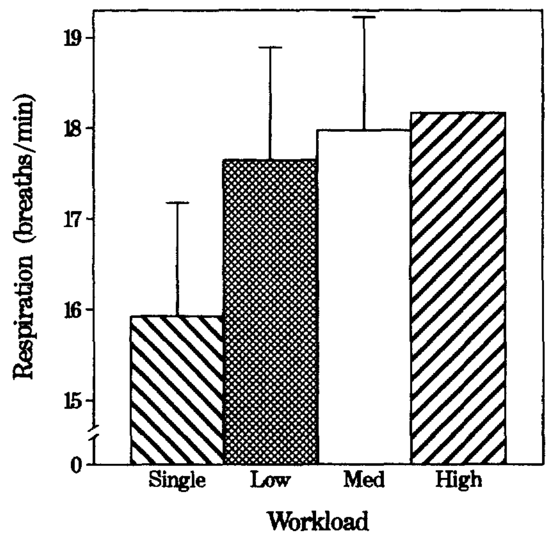

Fig. 9. Mean respiration rates during each of the four task conditions collapsed over both testing sessions (session 1 and 6). Error bars represent Tukey's HSD values.

conditions relative to the single task condition ($P < 0.05$).

3.7.3. Eye blinks

There was a main effect of workload for both blink duration ($F_{3,24} = 29.14$, $P < 0.001$) and blink amplitude ($F_{3,24} = 9.69$, $P < 0.001$). As shown in Figs 10a and b, respectively, blink duration was significantly shorter and blink amplitude was significantly larger in the multi-tasks relative to the single task ($P < 0.05$). Blink rate also showed a main effect of workload ($F_{3,24} = 30.75$, $P < 0.001$) and session ($F_{1,8} = 7.73$, $P < 0.02$). Fig. 10c shows that blink rate was significantly reduced during the multi-task conditions relative to the single task ($P < 0.05$). Blink rate was also higher in session 6 relative to session 1.

3.8. Subjective ratings

A composite mean score for ratings on the six workload sub-scales was evaluated (see Fig. 11). There was a main effect of workload only ($F_{2,16} = 13.60$, $P < 0.001$). Subjective workload was greater in the multi-task medium and high conditions relative to the multi-task low condition ($P < 0.01$). Counter to the behavioral data, subjects viewed task difficulty as equal across the medium and high workload conditions and did not believe workload decreased with training.

4. Discussion

The measures evaluated in this study (psychophysiological, peripheral physiological, behavioral and subjective) differed in their sensitivity to workload and training in our interactive tasks (see Table 1). All measures, except for respiration amplitude, distinguished between the single- and multi-task workload conditions. The influence of workload on these measures is congruent with previous reports in the literature (*behavior and subjective measures*: Eggemeier and Wilson, 1991; *ECG*: Grossman, 1992; Jorna, 1992; *respiration rate*: Wientjes, 1992; *blink rate*: Stern and Dunham, 1990; Brookings et al., 1996; *alpha power*: Earle and Pikus, 1982; *theta power*: Rugg and Dickens, 1982). However, only the behavioral, subjective, ECG, and alpha 2 power measures were sensitive to the different workload demands of the muti-task conditions, although they did not distinguish among all three of the multi-task workload conditions. The most effective measure of workload was behavioral performance since this measure was sensitive to the varying workload demands among all of the workload conditions. It is interesting to note that of the psychophysiological variables, only the continuous measures (both central and peripheral) were sensitive to workload manipulations in our multiple, interactive tasks. Alpha ERD and theta ERS were only sensitive to processing differences within our interactive, single task.

Contrary to expectations, alpha ERD and theta ERS were not effective measures of workload or training in our interactive multi-task conditions. Our subjects were continuously engaged in tracking and monitoring during the entire 3-min trial. Alpha power throughout the trial, including the prestimulus baseline, was greatly reduced due to the demands of these ongoing tasks. The lack of workload sensitivity for alpha ERD was due to the overall suppression of alpha activity which produced a floor effect masking alpha ERD. This

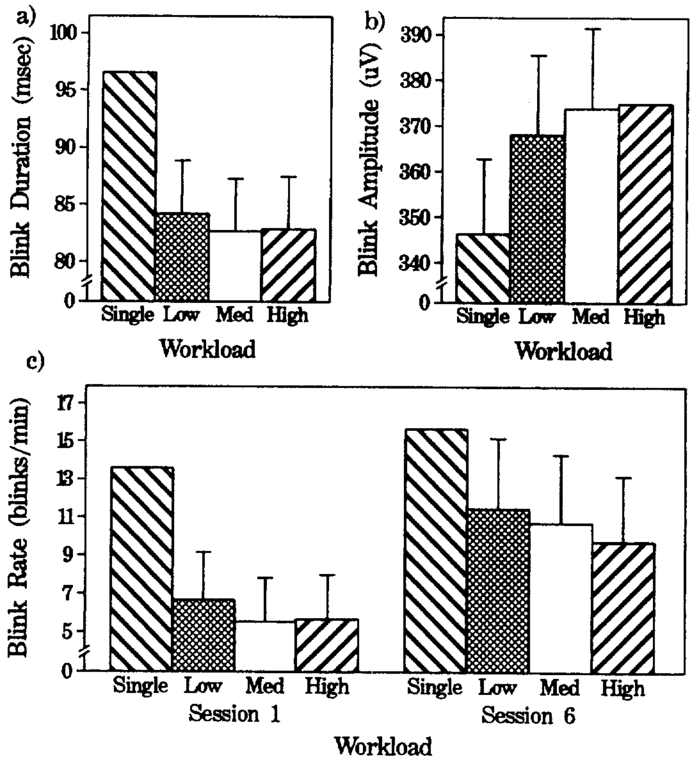

Fig. 10. EOG data during each of the four workload conditions collapsed over the two testing sessions (session 1 and 6). Panel (a) shows the eye blink duration; Panel (b) shows the blink amplitude; and Panel (c) shows the blink rate for the two testing sessions. Error bars represent Tukey's HSD values.

finding is consistent with the suggestion by Dujardin et al. (1995) that a task that is already very difficult may not show ERD when the task becomes even more difficult. The only exception to this floor effect was found for alpha 2 which had a lower prestimulus baseline power for the high relative to the low multi-task workload condition. The insensitivity of theta ERS to changes in multiple task difficulty is less clear. Perhaps a ceiling was reached with the low difficulty condition that could not be exceeded with further mental and behavioral demands.

Although alpha ERD was not sensitive to the different workload demands in our multi-task workload conditions, it was effective in measuring differences in processing demands in our single, interactive task condition. Consistent with previous research, alpha 1 ERD appeared to reflect alertness or attentional resource allocation, while alpha 2 appeared to reflect stimulus-related processing such as stimulus encoding, semantic encoding, and motor activity (see Pfurtscheller, 1988; Klimesch et al., 1992, 1996; Krause et al., 1994; Klimesch, 1996).

Alpha 1 ERD was found to occur during critical task information (i.e. correct/incorrect call sign, dial and frequency instructions) independent of whether this information required a response. Alpha 2 ERD also occurred during critical task information, but only when a response was required (i.e. dial and frequency setting instructions). The finding that alpha 1 ERD, but not alpha 2 ERD, occurred during the announcement of the call sign suggests that alpha 1 may be related to increased alertness or increased attentional allocation to specific stimuli. The call sign, which did not require an explicit response, served as a warning stimulus that preceded onset of task

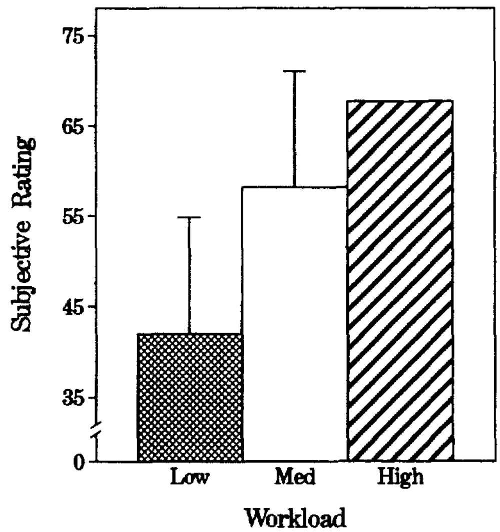

Fig. 11. Mean subjective workload ratings for the three multi-task workload conditions collapsed over the two testing sessions (session 1 and 6). Error bars represent Tukey's HSD values.

instructions. Encoding other task relevant information (i.e. dial and frequency setting instructions) should also solicit attentional resources. The finding that alpha 1 ERD became more widespread during dial and frequency instructions suggests that attention resource allocation may be especially high during this time period.

These findings and interpretations are consistent with results found in a visual–verbal task by Klimesch and colleagues (Klimesch et al., 1992; Klimesch, 1996). They found alpha 1 and alpha 2 ERD to occur during a task relevant stimulus, but only alpha 1 ERD occurred during the onset of a warning stimulus. In addition, alpha 1 ERD in our single task occurred mainly over parietal and occipital sites, with a left hemisphere emphasis. This is again consistent with findings by Klimesch et al. (1992) who found greatest alpha 1 desynchronization over parietal and occipital sites in a visual–verbal task. The left hemisphere emphasis of alpha 1 ERD in our task was not evident in Klimesch et al. study. Perhaps this ERD activity reflects resource allocation to language processing, since the left hemisphere is known to be involved in language and the communication event requires language processing.

Interestingly, we also found that frontal alpha 1 ERD occurred between 5.75 and 6 s in our study. During this time period, a command was given to set the navigation or communication dial to a specific frequency. This ERD may reflect the effortful process of planning or remembering the action to be carried out as indicated in the communication command. However, this interpretation is only speculative.

In short, our alpha 1 ERD findings suggest increased attentional resource allocation during critical task instructions, especially when the task instruction contained specific response information. Evidence that alpha 1 is *not* related to motor processing in our communication task is based on the absence of alpha 1 ERD over central and right central sites, even though left-hand responses were required to carry out instructions in the communication task.

Evidence that alpha 2 ERD may be sensitive to sensory-motor processing is based on the finding that alpha 2 ERD became more widespread over central, parietal, and occipital sites during time points in which motor activity and visual processing demands related to dial and frequency setting were high. The RT data showed that the correct dial was selected in approximately 5.19 s, and the correct frequency was set approximately 7.94 s, and the enter key was selected approximately 9.0 s after the start of the command message. Thus, high levels of motor activity and visual scanning would be expected to begin around 5.19 s. This is about the time alpha 2 ERD occurred widespread across central and parietal sites, followed 20 s later by widespread alpha 2 ERD at occipital sites. Consistent with these findings and interpretations, Pfurtscheller et al. (1994) showed alpha 2 ERD localized over occipital and central sites in a visual-semantic classification task that required right and left hand responses (right central for left-hand and left-central for right hand motor responses). Also, Klimesch et al. (1992) found alpha 2 ERD to occur maximally over parietal and occipital sites in a visual–verbal task during presentation of a stimulus that required a response.

In addition, alpha 2 ERD first occurred during dial setting instructions over right frontal–temporal and central sites, and occurred occasionally over left temporal sites. We can only speculate that alpha 2 ERD that occasionally appeared over left-temporal sites and right frontal–temporal sites in our task was related to auditory and/or perhaps semantic encoding of the communication message. This interpretation is consistent with past assertions that alpha 2 ERD may reflect stimulus-related processing and semantic encoding (see Krause et al., 1994).

Our theta measures were also somewhat sensitive to processing demands in our interactive tasks. Theta ERS, similar to alpha ERD, was effective in measuring differences in processing demands in our single, interactive task condition only. The later onset of significant changes in theta ERS (at some parietal, central and right frontal sites) to the communication task suggests that increased theta ERS may be associated with cognitive activity related to interpretation of the auditory message and not with the earlier occurring call sign recognition. In addition, theta FFT power was sensitive to differences between our multi- and single-task workload conditions. The findings of enhanced theta FFT with increased workload demands is congruous with other reports in the literature. However, the reported region of enhanced activity is less consistent. We found increased power over central, parietal and occipital sites in our multi-task conditions relative to our single task. Dolce and Waldeier (1974) reported increased parieto-occipital theta activity during a reading task compared to mental arithmetic. Rugg and Dickens (1982) found that their more difficult visuospatial task was associated with increased parietal theta activity than in their easier verbal task. Mecklinger et al. (1992) reported increased frontal and central theta activity during a semantic memory search task as memory load increased. Gundel and Wilson (1992) found increased left frontal activity to be associated with increased memory load. Furthermore, Gevins et al. (1988) also reported increased frontal theta with increased memory load. It is possible that single-task memory paradigms involve primarily frontal brain regions while the cognitive and behavioral demands required when performing multiple, concurrent tasks of increasing difficulty result in enhanced theta activity over posterior regions of the brain. Since most studies to date have only recorded EEG from restricted regions of the scalp it is difficult to speculate about theta topography. However, the data suggest that increased mental and behavioral task demands are associated with enhanced theta activity.

The only brain wave measure sensitive to workload differences among the multi-task conditions was alpha 2 power which decreased in the high relative to the low multi-task workload condition in the right centro-parietal sites. This greater alpha power suppression is likely due to the increased motor activity required by the left-hand to perform most of the monitoring tasks (i.e. light detection, gauge fault detection, and setting communication/navigation frequencies). This is consistent with previous research that has shown decreased alpha with increased task difficulty (e.g. Earle and Pikus, 1982). Our finding suggests that response demands related to the monitoring tasks above were greater in the multi-task high relative to the multi-task low workload conditions. No evidence was obtained suggesting that this measure was sensitive to any other workload, processing demands between our multi-task workload conditions.

Alpha 2 power also was effective in measuring workload differences between the multi- and single-task workload conditions. The main decreases in alpha 2 power for the multi-tasks compared to the single task occurred at mid-line parietal, mid-line central, left central sites, mid-line occipital, and right occipital sites which suggest that the main workload differences between these tasks may be related to motor responses and visual monitoring. Tracking (right hand) and visual monitoring of the lights and gauges (upper left of the visual display) only occurred in the multi-task conditions. The topographical decreases in alpha 2 power for the multi-task conditions relative to the single task appear to reflect the tracking responses by the right hand (mid and left central sites) and visual monitoring (mid parietal, mid occipital and right occipital). These findings provide further support that alpha 2 is sensitive to sensory-motor processing in our tasks. Alpha 1 power did a poorer job distinguishing between multi- and single-task workload conditions showing relative power decreases for the multi-task condition in the central and left occipital sites only. It could be that alpha 1 was generally sensitive to the processing demands in both our single and multi-task conditions.

Training effects were found only for behavioral performance and eye blink rate. It is possible that workload did not decrease with only five training sessions since there was no indication that performance was beginning to asymptote in any of the task conditions. Also, subjects did not perceive workload to decrease with training. Perhaps the improvement in performance and increases in blink rate with training reflected strategic changes, especially in the high workload conditions. Wickens (1992) suggests that a change in strategy could lead to increased behavioral performance, while not necessarily affecting other physiological measures.

In summary, alpha ERD and theta ERS do not appear to be effective measures of workload or training in continuous, interactive, multi-task environments. However, they appear to be effective measures of cognitive and motor processing in an interactive, single task. The most effective measures of multi-task workload in our study were ECG and behavioral performance. Finally, alpha 2 power did discriminate between the low and high multi-task workload conditions, and these findings suggest that increased motor processing demands related to the monitoring tasks (with the possible exception tracking) may be responsible for the decrements in performance found across our workload conditions.

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