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THE EFFECTS OF ONE NIGHT'S LOSS OF SLEEP AND RECOVERY ON PHYSIOLOGICAL, PERFORMANCE, AND SUBJECTIVE INDICES (U)

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The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Regulation 169-3.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

KENNETH R. BOFF, Chief
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13. ABSTRACT *(Maximum 200 words)*

The effects of one night's sleep loss were tested on subjects who were tested again after a night's recovery sleep. Several physiological measures were taken while subjects were administered the AGARD STRES Battery (to assess performance changes) and the NASA-TLX (a subjective index). In general, all measures showed changes with sleep loss which then recovered with one night's sleep. On several of the STRES Battery tasks, reaction times increased and accuracy decreased after a night without sleep, and then recovered with a night's sleep. Tracking performance especially was consistently affected. Blink rate reliably increased with a night's sleep loss, and recovered with sleep; blink duration tended to increase with sleep loss. Heart rate decreased with sleep loss, while heart rate variability at high and medium bands was found to increase consistently. Power in the EEG alpha band tended to be greater after a night's loss of sleep when it was measured in terms of absolute power and as relative to total EEG power. Evoked potential results were equivocal. Subjectively, subjects ranked the individual STRES Battery tasks as harder after a night without sleep. Just one night without sleep affected task performance, physiological measures, and subjective assessments of task requirements; recovery generally occurred with one night of sleep.

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INTRODUCTION

Sustained flight operations often require military aviation personnel to operate complex systems for prolonged periods of time without sleep. To maximize operator performance under such conditions, some index of the resulting decrement needs to be tracked as duties are performed, and an adjustment made to the operator or to the environment, when the value of that index exceeds some established level. Central to this approach is the creation of such a quantifiable index, which must indicate when performance is approaching an unsafe level due to sleep loss or fatigue. Studies of the effects of sleep loss on task performance have produced equivocal results, especially for deprivation at moderate levels. The goal of the current study was to use a standardized test battery to assess effects of sleep loss and recovery on performance, and to employ a variety of physiological measures and a subjective index to determine if there would appear an early indicator of sleep loss, evident before performance was affected.

The effect of sleep loss on pilot performance has been investigated with F/A-18 aviators (Shappell and Neri, 1993) and S-3 aviators (Neri and Shappell, 1993), and in other military and commercial flight settings (Hawkins, 1978; Green, 1984; Farmer and Green, 1985; Graeber, 1988, 1989; Neri, Shappell, and DeJohn, 1992; Cabon, Coblentz, Mollard, and Fouillot, 1993). Train-handling performance effects with sleep loss have been documented by Cabon et al. (1993) and Kuehn (1993). Long-haul truck driving with sleep loss has been investigated (Mackie and Miller, 1978; Moore-Ede, 1993) as have continuous and sustained operations (CONOPS and SUSOPS, Krueger, 1989; Stretch and Jamieson, 1990).

In the laboratory, the effects of sleep deprivation have been investigated in terms of task performance (see Kleitman, 1963; Wilkinson, 1965; and Johnson, 1982, for reviews) and physiology (see Horne, 1978a, 1988 for reviews).

Many hours without sleep has long been known to cause performance decrements (Patrick and Gilbert, 1896; Robinson and Hermann,1922); but moderate deprivation of about 24 hours without sleep has produced equivocal results. Research indicates that when over 100 hours of deprivation are incurred, significant performance effects are seen. Katz and Landis (1935) described delusions, irritability, and an inability to perform certain cognitive tasks with up to 231 hours without sleep. Memory test performance worsened after 72 hours without sleep for some of the subjects in an experiment conducted by Edwards (1941); performance on a tracking task, a similarities and logical puzzles test, a short-term memory test, and an interaction test deteriorated as time without sleep increased up to 205 hours (Pasnau, Naitoh, Stier, and Kollar, 1968).

In contrast, with only one night's loss of sleep, performance effects are not often manifested. A serial reaction time task employed by Farmer and Green (1985) required pilots to indicate on which of four locations on a monitor a stimulus had been presented. One night's sleep loss resulted in significantly increased response times but no change in response accuracy. Farmer and Green found no increased reaction time with sleep loss to a grammatical reasoning task, whereas Schlegel, Gilliland, and Schlegel (1986) found significant increases in response time to this same task. Schlegel, Gilliland and Schlegel found increased reaction time to all levels of difficulty on a math test with one night's sleep loss, but found no effect of sleep loss on accuracy. Similarly, these authors found increased response time to memory search, spatial processing, and grammatical reasoning tasks with sleep loss, and found no effect on accuracy. Many experiments indicate increases in reaction time, movement time, number of hits/detections, and number of lapses, but other studies reveal no change in error rate, movement error, or number of omissions. Polzella (1975) examined the effects of 24 hours' sleep deprivation on short-term recognition memory using a probe-recognition paradigm. After sleep loss, d' (the indicator of sensitivity used to estimate the strength of an item in memory) was significantly reduced, although reaction time was not affected, except to be more positively skewed. It was suggested that the occurrence of lapses increased with sleep deprivation, and that these lapses were accompanied by memory deficits. These lapses disrupted the encoding of the stimuli into short-term, and subsequently long-term, memory.

This disparity of results for sleep loss at moderate levels has not been adequately evaluated. Comparisons across experiments reveal enormous task differences, confounding with circadian rhythm, training inconsistencies, varying time-on-task, and the use of additional stressors. Neither does the investigation of sleep loss seem to have taken into account the several stages of cognitive processing in a systematic way. The use of the AGARD STRES Battery in the current effort was motivated by the need to employ a standardized measure which would tap several aspects of cognitive processing, such as stimulus identification, central processing, and motor output. Developed by the Advisory Group for Aerospace Research and Development (AGARD) Aerospace Medical Panel (AMP) Working Group 12 (AGARD AMP Working Group 12, 1989) to provide a standard battery of performance tests for applied researchers, the battery's criteria for test selection emphasized strong reliability, validity, and sensitivity and a solid psychometric history in assessing stressor effects. The consensus of this working group and other researchers is that there are three primary stages of information processing: perceptual input, central processing and motor output (or perception, decision-making, and action). In the AGARD battery, some of the reaction time tasks tax the perceptual resources, especially when the stimuli are presented as visually degraded. Central processing resources are essential to the performance of memory, mathematical processing, spatial processing, and grammatical reasoning tasks, while the tracking task and the double-response and inverted response reaction time tasks utilize motor output resources. Another consideration in choosing this battery to assess the effects of sleep loss and recovery on performance is that it takes about an hour to administer, since a test of short duration may not allow manifestation of the performance effects of sleep loss. Sleep deprived people can often exert just enough effort to perform normally for a short period of time. As Johnson (1982) states, "The longer the task, the more sensitive it is to total sleep deprivation." To overcome the objection that putting forth an effort for a brief moment might be enough to overcome the effects of sleep loss could be responsible for the lack of performance effects with moderate sleep deprivation, the STRES battery does incorporate a tracking task, which requires continuous, sustained effort, and employs a number of tests, including two dual-task components. It was felt that by assessing the effects of sleep loss on a standardized battery which requires the resources of several aspects of cognition, and viewing physiological and subjective as well as performance variables, a better sensitivity to moderate sleep loss would be shown. Also of interest was whether these same parameters would be sensitive to recovery after a normal night's sleep.

Physiologic studies of sleep loss have measured many variables: skin conductance, electrical activity of the brain and muscles, circadian rhythm (Horne and Ostberg, 1977), biochemistry (e.g., glucose, adrenaline, cortisol), thermoregulation, respiratory activity, eye movements, and cardiovascular activity (Horne, 1978b). Since the current experiment focuses on electroencephalographic, eye blink, and cardiac activity, the following section reviews literature pertaining only to those variables.

In the absence of a task, EEG after sleep loss often shows reduced alpha and increased theta. Assessing EEG during thirty hours without sleep, Comperatore, Caldwell, Stephens, Chiaramonte, Pearson, Trast, and Mattingly (1992) found increased theta and some evidence of decreased alpha. Naitoh, Kales, Kollar, Smith, and Jacobson (1969) assessed EEG every six hours of a 205-hr deprivation study, with eyes closed or eyes open. Alpha dropped substantially until about 120 hours, and then recovered slightly. Relative delta and theta began to rise at about 70 or 80 hours of deprivation, and leveled off at about 120 hours. Pigeau, Heslegrave, and Angus (1987) documented increased delta and theta over 64 hours without sleep. Sleep deprivation also typically leads to reduced alpha when there is a task required of the subject, for instance, to stand (Armington and Mitnick, 1959; Rodin, Luby, and Gottlieb, 1962; Naitoh et al., 1969). Williams, Lubin and Goodnow (1959) and Armington and Mitnick found that, after sleep loss, a counting task depressed alpha more so than did adding, or instructions to keep a blank mind.

Evoked potentials provide information about brain processes which is time-locked to stimulus presentation. Harsh and Badia (1989) found that with 48 hours of sleep deprivation, N2 latency, elicited by an auditory oddball paradigm, covaried with performance effects on the Walter Reed Performance Assessment Battery, indicating that this EP component likely represents central processes that change with sleep loss. Krull, Smith, Sinha, and Parsons (1993) found increased N1 latency to a simple visual RT task with 30 hours of sleep loss, and interpreted these findings in terms of slowed initial stimulus detection due to sleep deprivation. With thirty hours of sleep deprivation, Comperatore, Caldwell, Stephens, Chiaramonte, Pearson, Trast, and Mattingly (1992) found changes in a middle latency auditory evoked response, with increased amplitude and latency perhaps representing degraded alertness or changes in neural activity due to sleep loss.

Inconsistent findings appear in the literature regarding sleep deprivation effects on heart rate. The debate over whether subjects should be tested for heart measures in an active or passive state is discussed by Wilkinson (1965) and others, who are concerned that testing a passive subject might result in a measure of sleepiness while measuring an involved subject produces a measure of the difficulty of staying awake (Horne, 1978b). Naitoh, Pasnau, and Kollar (1971) found decreased resting heart rate with sleep deprivation of 170 hours, as did Corcoran (1964) at 60 hours. Also finding decreased heart rate at rest with sleep loss were Scrimshaw, Habicht, Pellet, Piche, and Cholakos (1966). By contrast, increased heart rate at rest with deprivation was reported by Koranyi and Lehmann (1960) and Johnson, Slye, and Dement (1965). Fenz and Craig (1972) also found increased heart rate with sleep deprivation when heart rate was measured during task performance. Froberg (1977) found no clear trend in heart rate with subjects who were seated at rest with 72 hours of sleep deprivation, nor did Horne (1978b), whose subjects were performing a tracking task.

Heart rate variability (HRV) is a measure which represents the beat-to-beat fluctuations of the heart rhythm (Mulder, 1986), and its analysis generates three distinct bands with different postulated underlying physiological bases: a low frequency band originating from the regulation of body temperature, and mid-range band related to short-term blood pressure regulation, and a high frequency band, representing momentary respiratory influences on heart rate. It has been seen to decrease under conditions of high mental loading and to increase with decreased attention (Kalsbeek, 1970); discrepant findings are discussed by Wilson (1992). Ax and Luby (1961) found decreases with sleep loss, while a different measurement technique used by Horne (1978b) generated increases in heart rate variability with sleep loss.

Subjective measures of sleepiness or ability to concentrate often correlate with task performance in sleep loss experiments (Akerstedt, Froberg, Friberg, and Wetterberg,1979), and mood changes can be the earliest detectable effect of sleep loss (Bonnet, 1994). The current study employed the NASA-TLX (Hart and Staveland, 1987) as an indicator of subjective workload, to determine if perceptions of task difficulty changed with sleep loss. It may be that sleep loss makes one feel that more effort is required to complete a task, or that one must work harder to perform cognitive tasks when one has been deprived of sleep.

The current study attempts three goals: to evaluate performance, physiological, and subjective changes with one night's sleep loss and again after a night of recovery sleep, relative to the stage of processing required by each task; to use a standardized battery of performance tasks which has been widely used and for which there are a great deal of existing data to assess the performance changes; and to determine a relationship among subjective, physiological and performance effects of sleep deprivation.

METHODS

Subjects

Subjects were eleven male college students, between the ages of 18 and 30 years and were paid for their participation. Subjects were required to be in good health and to be without drug and/or alcohol dependency, and were chosen on the basis of normal sleep habits (they typically went to sleep between 10 pm and midnight and arose between 7 and 9 am). Subjects were right-handed and had normal or corrected-to-normal-vision (there were no contact lens wearers). Subjects refrained from consuming alcohol during the week of the experiment and were required to keep a food and sleep diary for the week prior to and the week of the experiment.

Design

The variable of interest is rested vs sleep deprived conditions. This paper reports data from three of six experimental sessions: Session 2 (after a night's sleep), Session 4 (after 24 hours without sleep), and Session 5 (after a night's recovery sleep). (Performance data for all six sessions can be found in Gravelle, 1993.) Figure 1 is a timeline of the experiment and indicates the sessions analyzed here. Of interest are the physiological, performance, and subjective data and how they varied with sleep loss and recovery.

The STRES Battery was administered six times over sessions in which the subjects were in a normal or sleep-deprived state. As the tests were administered, several physiological measures were taken. A three-minute baseline before and after the test battery was also used for the collection of physiological data. During this time, subjects were instructed to close their eyes. Subjects completed the NASA-TLX after each experimental task and indicated the level of difficulty experienced in performing that task relative to six scales: mental demand, physical demand, temporal demand, own performance, effort, and frustration.

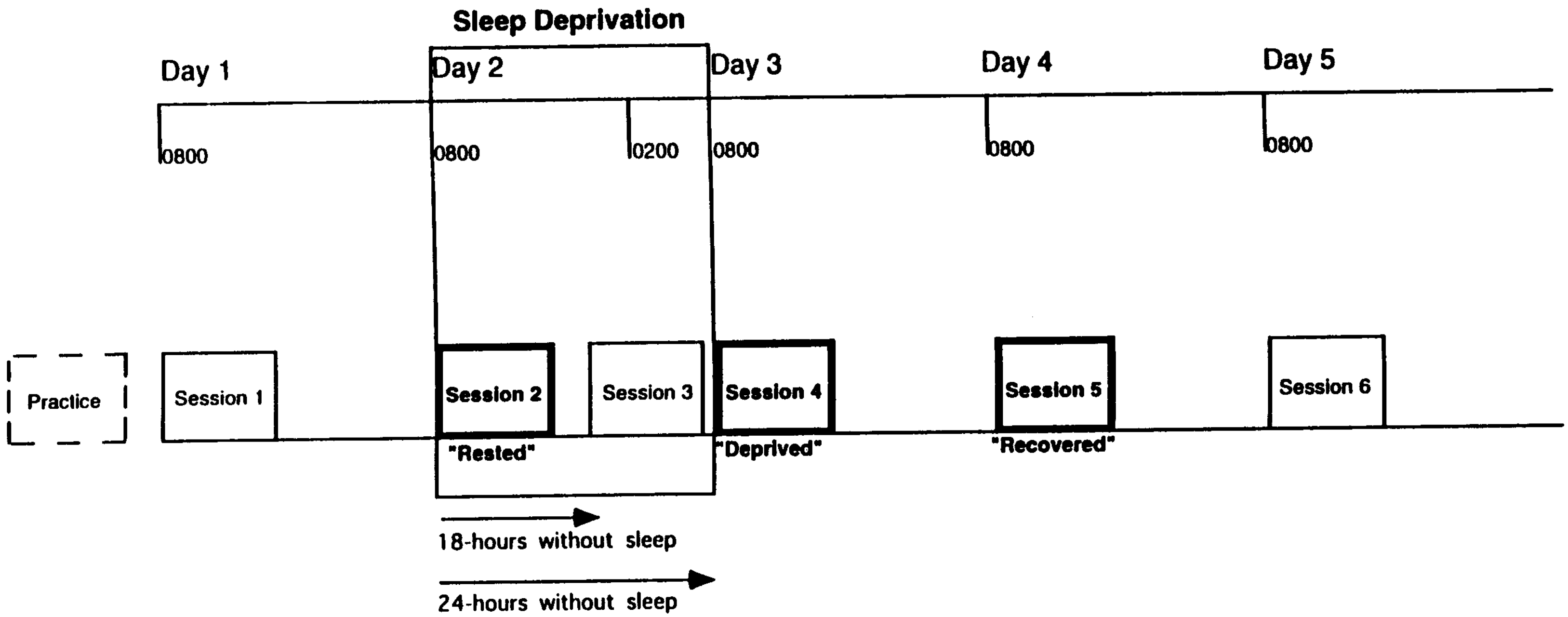


Figure 1. Timeline of experimental sessions and experimental conditions: rested, deprived, recovered.

Procedure

The experimental procedure was administered three times, in separate two-week blocks, one for each of the three groups of subjects (N=4, N=4, N=3). Each time the experiment was run, it involved five days, as outlined below. The experimental groups were all treated identically. The test battery was administered to two subjects at a time, with subjects being assigned a time when testing started each day of 800 hours or 1030 hours The individual tests were randomized and counterbalanced into two presentation orders which were divided equally among subjects. Half the subjects performed the reaction time and grammatical reasoning tasks first while the remaining subjects started the session with memory set, math, tracking, dual, and spatial tasks. At this point, subjects switched computers and performed the remaining tasks. Which group of subjects started with the reaction time tasks was varied over sessions.

Subjects participated in a separate training session following AGARD guidelines of about six hours in which they became familiar with the STRES Battery Tests and achieved a stable level of performance (AGARD AMP Working Group 12, 1989). They also learned to complete the NASA-TLX, which required them to indicate the difficulty of each of the experimental tasks, and to weight each task. Subjects were assigned to a daily testing time (0800 hours or 1030 hours); the STRES Test Battery was administered at this time for the duration of the experimental sessions. The sessions were as follows and the timeline illustrating them is seen in Figure 1.

Session 1 Thursday	Subjects were tested at their assigned time for about 75 mins in a normal rested condition
Session 2 Friday	Subjects were tested for about 75 mins in a normal rested condition and were asked to not sleep during the rest of the day; subjects returned to the lab at 2200 hrs and stayed awake all night
Session 3 Saturday	Subjects were tested after 18 hours of sleep

	deprivation (assigned test times were adjusted for this session)
Session 4 Saturday	Subjects were tested after 24 hours of sleep deprivation and were instructed to get a normal night's sleep
Session 5 Sunday	Rested subjects were tested
Session 6 Monday	Rested subjects were tested

An experimental session began with the subjects being instrumented for physiological recording. After the electrodes were applied, subjects performed the STRES Battery in groups of two, with each of two computers being dedicated to a specific set of tests (Computer A: Reaction Time Tasks and Grammatical Reasoning and Computer B: Unstable Tracking, Memory Search, Dual Tasks, Spatial Processing, and Mathematical Processing Tasks). Tests were prefaced by the presentation of instructions on the computer monitor. Subjects were presented the tests in the sequence specified by their group assignment. Performance data were stored on the computers. After each experimental task, subjects completed the NASA-TLX ratings. About halfway through the experimental session, subjects switched computers and completed the remainder of the tests. After the tests were administered, the electrodes were removed and instructions for the following day were given.

Performance Measures

The AGARD Standardized Tests for Research with Environmental Stressors (STRES) Battery was used to assess subjects' rested and sleep-deprived performance. The battery includes these tests: reaction time (RT1=basic, RT2=coded with degraded stimuli, RT3=time uncertainty, RT4=double responses, RT5=response inversion, and RT6=basic), mathematical processing, memory search at two levels of difficulty, spatial processing, unstable tracking, grammatical reasoning,and dual-task (unstable tracking concurrent with each of two levels of memory search). Figure 2

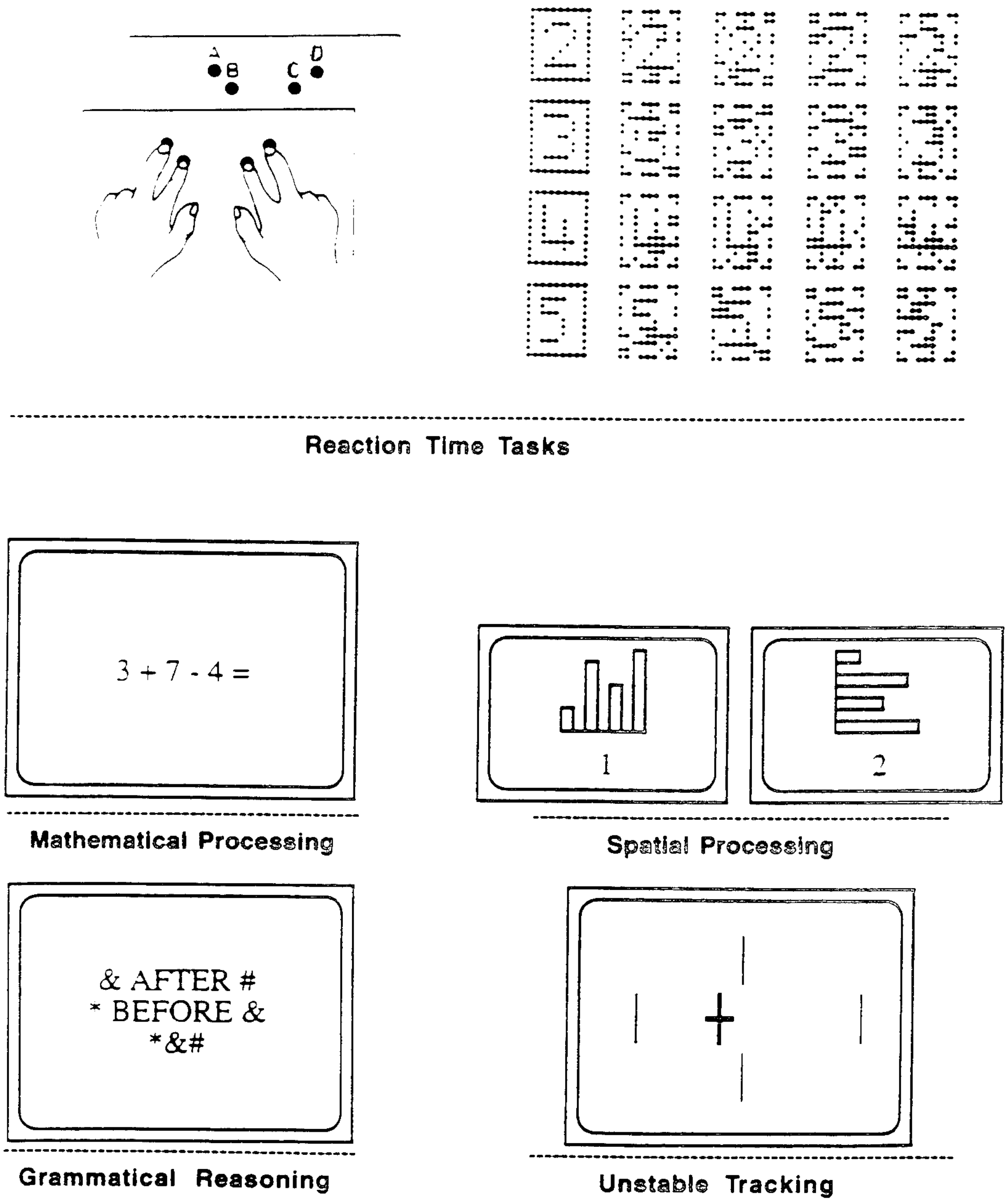


Figure 2. Stimuli presented to subjects for STRES Battery tasks. Finger arrangements and degraded stimuli (RT 2) are shown at the top of the page.

represents the stimuli presented in these tasks and shows the response device and finger positions. The reaction time tasks were delivered in 2-min blocks of 60 trials each. The memory search tasks were administered in blocks of 2 min each for each set size (2 or 4 letters). The remaining tasks were all presented for 3 mins. Reaction times and accuracy scores were gathered for the reaction time, mathematics, grammatical reasoning, memory search, and spatial processing tasks. Total RMS error and number of resets (the system repositioning the cursor after a boundary error) were calculated for the tracking tests. (For details about these tests, see the AGARD AMP Working Group 12,1989.) Tests were administered on a Zenith 248 computer; a Data Translation 2808 analog-to-digital board and an OEM Controls, Inc. joystick (M54M 5705) were used. Micro Experimental Laboratory software (MEL Version 2.0, third-generation integrated software system, Schneider, 1988) was used to present stimuli and to record and later analyze performance data.

Physiological Measures

Electrophysiological recording was done for EEG, EOG, and EKG, using the Psychophysiological Assessment Test System (PATS, see Wilson and Oliver, 1989, 1990). Three leads were connected for EEG; silver/silver-chloride electrodes were placed according to the International 10-20 system (Jasper, 1958) to record at Cz, Pz, and Oz. Two silver/silver-chloride electrodes at the mastoids acted as reference. Signals were amplified by a factor of 50000 (Grass Instruments amplifier model P511K) with a band-pass of 0.3-30 Hz

EOG was monitored through two electrodes, one centered above the left eye and one centered below it. Signal amplification was set at 5000 and the band pass was 0.3-100 Hz.

Recording electrodes for heart activity were placed on the sternum and on the fifth intercostal space on the left side of the body. Signals were amplified by 2000 with a band-pass of 10-100 Hz. All electrodes were grounded via a lead placed on the right side of the ribcage in the fifth intercostal space.

Physiological Measures/Quantification

EPs: Evoked potentials were averaged from segments of EEG records which included the presentation of a task stimulus to generate the evoked potential. Epochs were 900 msec long, and consisted of a 100 msec prestimulus baseline and an 800 msec poststimulus period. The sampling onset was started by a pulse time-locked to the display and synchronized with the raster. EP waveforms were decimated to 200 Hz and corrected for eye movements via the PATS. Trials containing EOG greater than +75 microvolts or less than -75 microvolts were excluded from further analysis. ERP waveforms were then averaged per subject per session per task. Measurement of peak latencies and amplitudes were obtained after latency windows were selected from the averaged waveforms. Of interest were N1 (70-160 msec), P2 (165-280 msec) and P3 (285-460 msec).

EEG: Electroencephalographic records were decimated to 100 Hz and corrected for eye movements (Gratton, Coles, and Donchin, 1983) via the PATS. EEG was analyzed by these bands:

delta	1.5-3.5 Hz
theta	4.0-7.5 Hz
alpha	8.0-13.5 Hz

Heart Rate/Variability: Heart beats were identified through the PATS Heart Rate Analysis program, using the amplitude/slope method of heart beat detection. Time intervals between successive R waves were determined by PATS and outliners were corrected. Interbeat intervals were additionally processed through a Porges-Bohrer filter (Porges and Byrne, 1992) to determine heart rate variability at filter settings of medium (0.06-0.14 Hz) and high (0.15-0.40 Hz).

EOG: The PATS identified blinks, then the record was reviewed and edited if necessary. Blink amplitude, rate, and duration were calculated; the 50% window duration was used for the duration measure (Stern and Dunham, 1990).

Subjective Measures

The NASA Task Load Index (NASA-TLX) (Hart and Staveland, 1987) was administered after each STRES task was completed. Ratings on six subscales (mental demand, physical demand, temporal demand, own performance, effort, and frustration) were weighted and averaged to generate an overall workload score for each of the experimental tasks. The weighting factor was determined by having the subject choose between pairs of the factors according to which was more important in determining workload. Following each task, subjects indicated the magnitude of each dimension for each task by marking a scale, represented as a 12-cm line divided into 20 increments, with bipolar descriptors (e.g., high/low) on either end.

RESULTS

To address the main question of interest, the effects of sleep loss on performance measures, physiological variables, and subjective assessments, t-tests were conducted between Sessions 2 and 4. Additional t-tests between Sessions 2 and 5 were used to determine if recovery occurred with one night's sleep. In order to select variables of future interest to investigators who evaluate the effects of sleep loss, a .05 level of probability was used.

Performance over Sessions

Performance measures include reaction time, standard deviation of reaction time, accuracy (percent correct responses) and the standard deviation of accuracy for reaction time tasks, mathematical, grammatical, spatial, and memory tasks, and the memory task component of the dual tasks. Tracking, as a single task, and as a component of the dual tasks, resulted in two measures: total RMS error and number of resets. Subjects' tracking performance was accurate enough so that few resets ever occurred. Analysis of number of resets produced no significant findings and is not addressed further.

Figures 3 through 6 plot changes in performance measures for all tasks as a function of session. General trends are clear from these plots, with Figure 3 showing increased reaction time between Sessions 2 and 4 and then decreasing reaction times for Session 5 for all tasks except spatial processing. Accuracy of response, as depicted in Figure 4, decreased between Sessions 2 and 4 and then tended to increase for Session 5. The variability of reaction time (Figure 5) increased with sleep loss and decreased with a night's recovery sleep. Figure 6 shows the significant increases in total RMS error during the tracking task with sleep deprivation, and the recovery in tracking performance at Session 5.

Significant differences were found between Sessions 2 and 4 for many of these

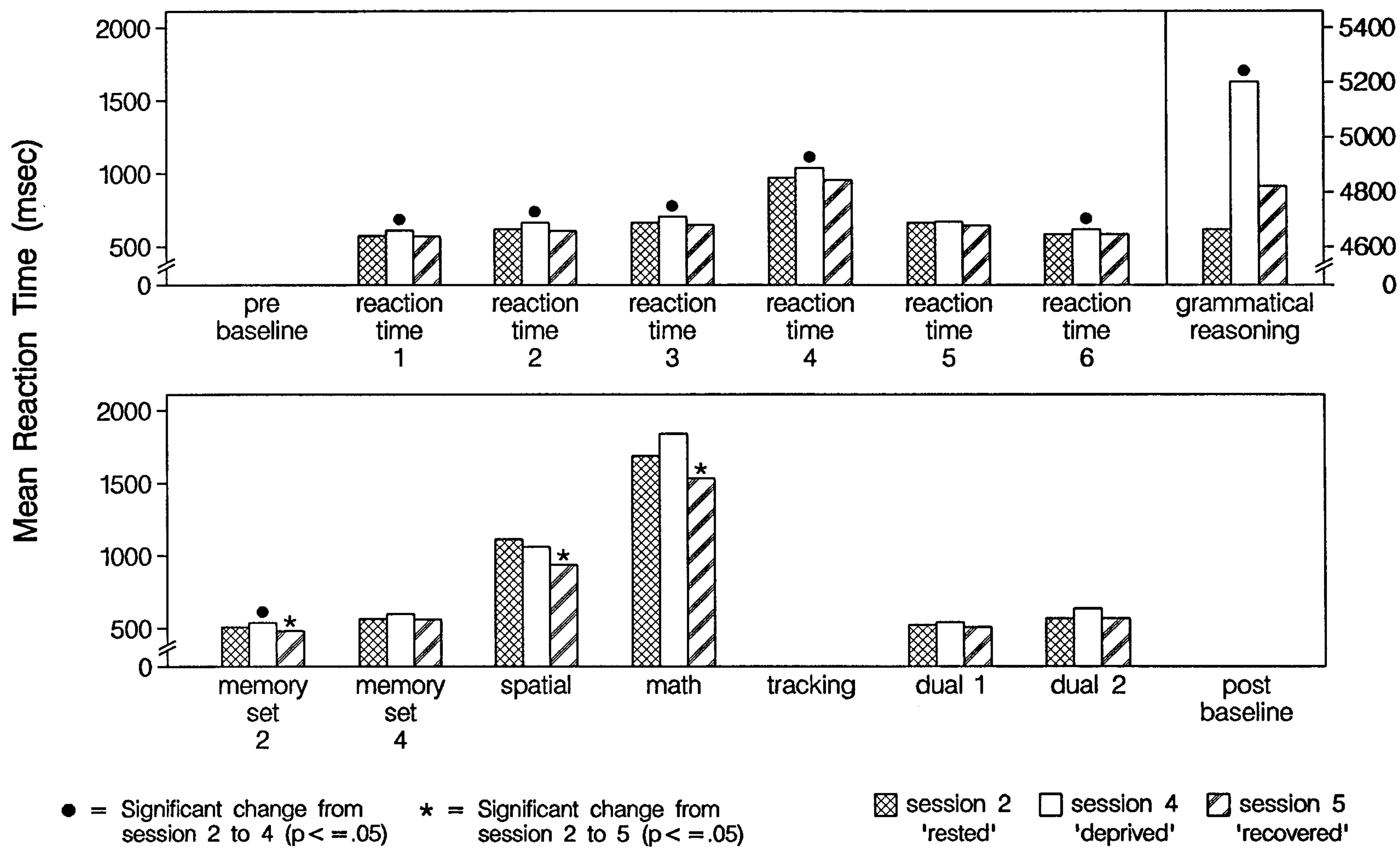


Figure 3. Mean reaction time for STRES battery tasks over sessions.

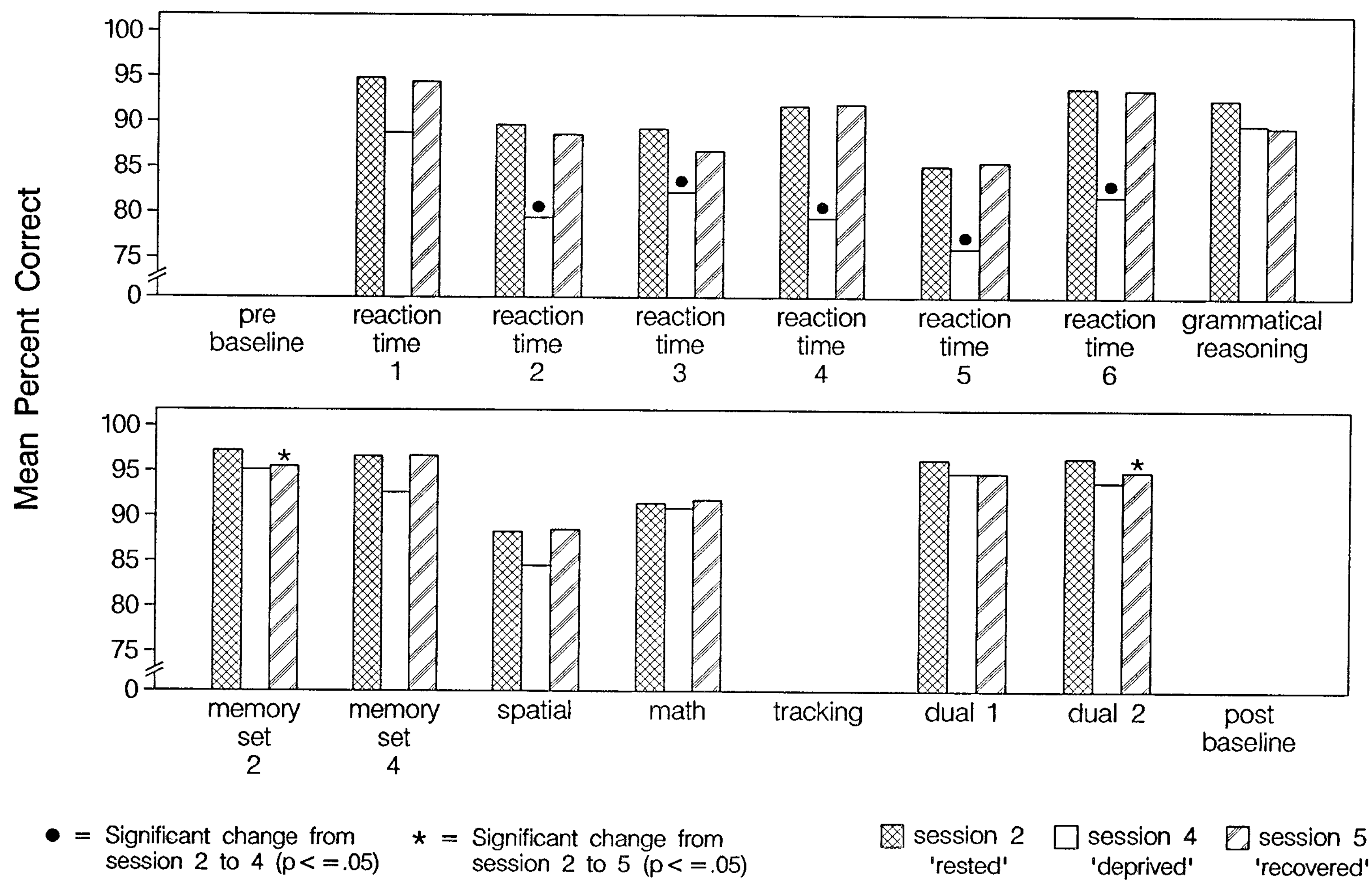


Figure 4. Mean percent correct responses for STRES battery tasks over sessions.

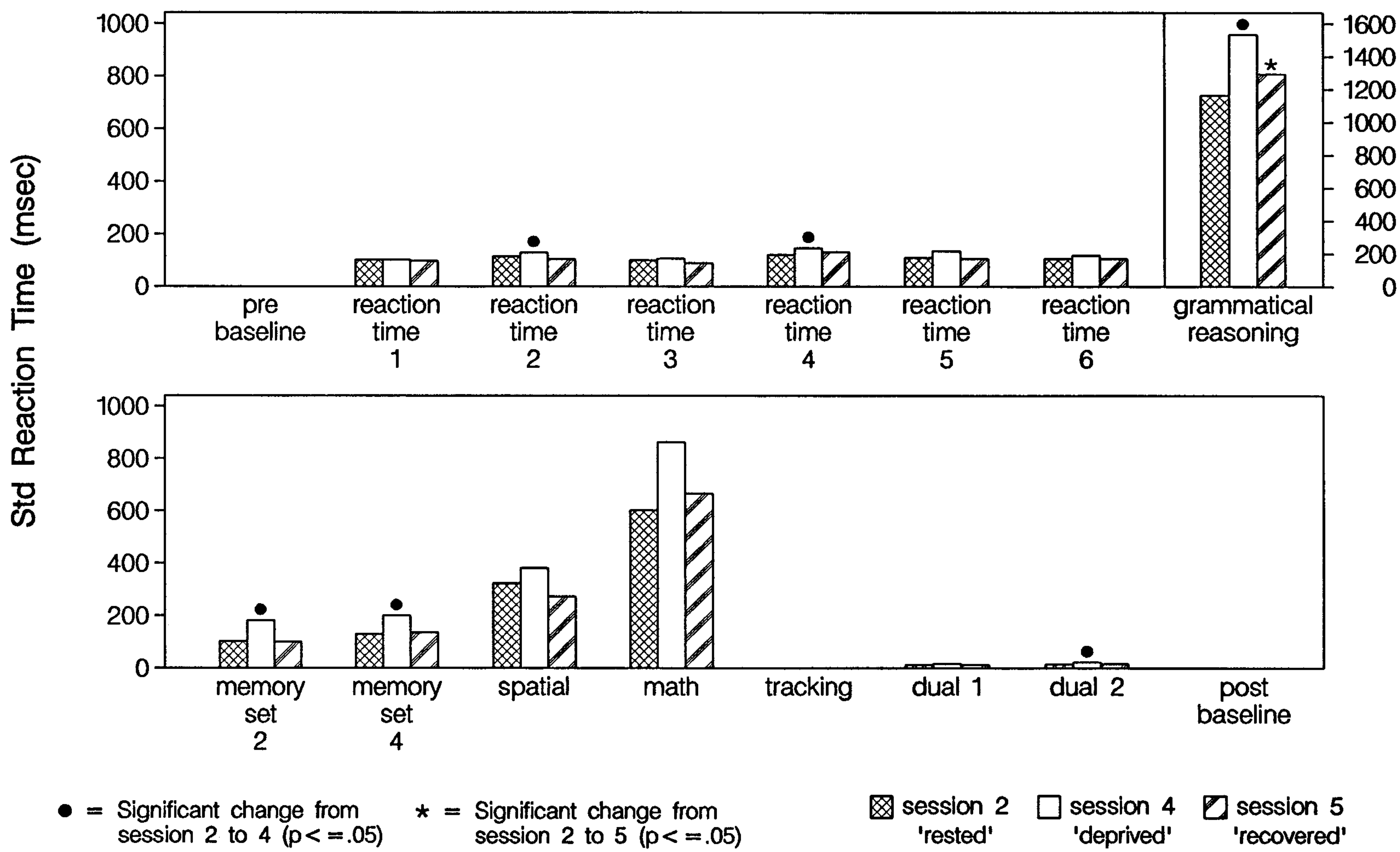


Figure 5. Mean standard deviation of reaction time for STRES battery tasks over sessions.

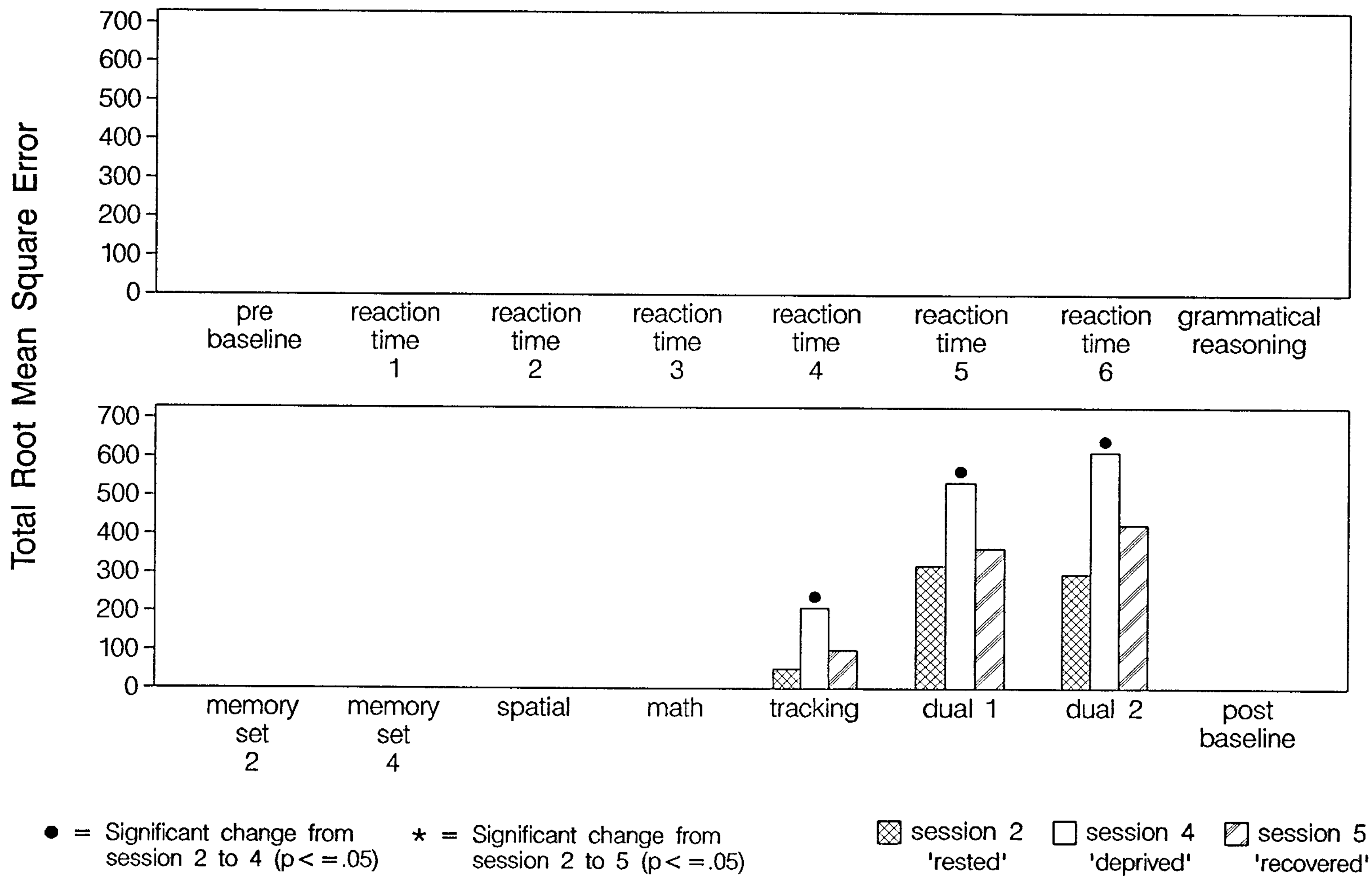


Figure 6. Total root mean square error for STRES battery tracking tasks under both single and dual task conditions over sessions.

performance measures for certain tasks. The dots above the histograms' bars in Figures 3-6 and in the matrix displayed as Figure 7 indicate which experimental task/performance-measure combinations produced a significant difference between Sessions 2 and 4. Reaction times increased significantly for RT 1 ($t=2.319$; $p=.0428$), RT 2 ($t=2.745$; $p=.0206$), RT 3 ($t=2.691$; $p=.0227$), RT 4 ($t=3.607$; $p=.0048$), RT 6 (t-3.271; $p=.0084$), and grammatical reasoning ($t=4.033$; $p=.0024$). The variability of reaction time increased significantly for RT 2 ($t=2.298$; $p=.0444$), RT 4 ($t=2.637$; $p=.0248$), grammatical reasoning ($t=3.513$; $p=.0056$), MS 2 ($t=3.291$; $p=.0081$), MS 4 ($t=3.078$; $p=.0117$), and the memory component of Dual Tasks 2 ($t=2.379$; $p=.0387$). Accuracy significantly decreased for RT 2 ($t=-2.458$; $p=.0338$), RT 3 ($t=-2.232$; $p=.0497$), RT 5 ($t=-2.300$; $p=.0443$), and RT 6 ($t=-2.722$; $p=.0215$). Total root mean squared error (RMS) increased significantly for the single tracking tasks between Sessions 2 and 4 ($t=4.240$; $p=.0017$), and for the tracking component of Dual Tasks 1 ($t=3.233$; $p=.0090$) and Dual Tasks 2 ($t=3.125$; $p=.0180$).

With a night's recovery sleep, Session 5 performance closely resembled that of Session 2. The boxes in Figure 7 indicate which task/performance measure combinations did not recover completely. Performance on Session 5 differed significantly from Session 2 for reaction time on mathematics and spatial processing tasks ($t=-3.091$; $p=.0144$ and $t=-3.232$; $p=.0090$, respectively). Accuracy did not recover completely for MS 2 ($t=-3.540$; $p=.0054$) and for the memory component of Dual Tasks 2 ($t=-3.135$; $p=.0106$). Total RMS error recovered completely by Session 5 for the tracking task under both single and dual conditions.

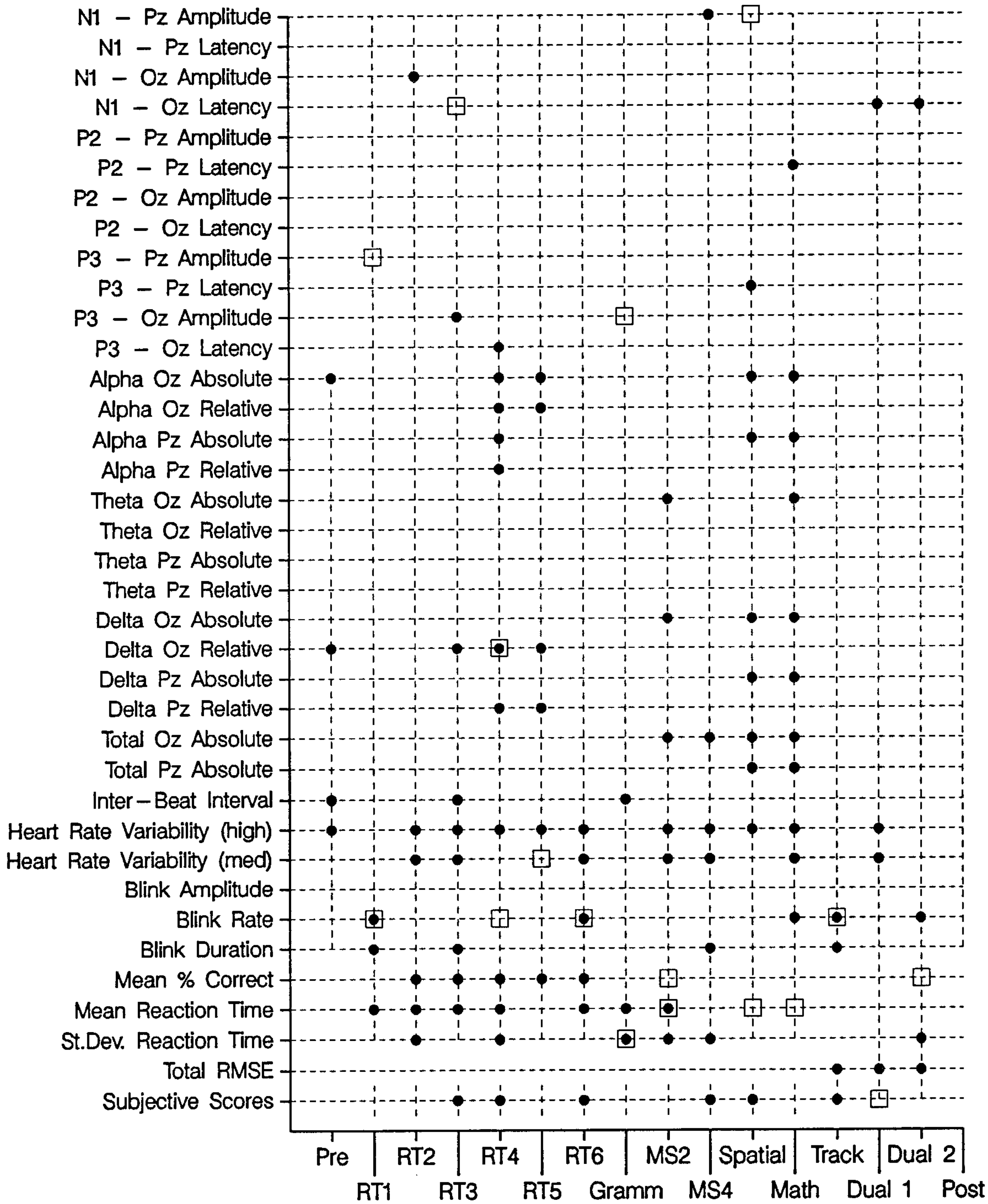
Physiological Variables over Sessions

Physiological variables which were analyzed by t-tests between sessions include electroencephalogram (EEG) bands at Oz and Pz, the amplitude and latency of three evoked potential components (EPs), heart rate, two bands of heart rate variability (medium and high), eye blink rate, eye blink amplitude, and eye blink duration. For reaction time tasks, the entire two-minute testing period was used in these analyses. For the remaining tasks, the middle two minutes were parceled from the test file and used for analysis of physiological variables.

EEG

Figures 8 through 15 show the general trends for absolute power of EEG bands at Pz and Oz over sessions. Total power increased from Session 2 to Session 4 at both Oz and Pz, as is shown in Figures 8 and 9, and this is reflected by a tendency toward greater power for Session 4 in alpha, delta, and theta bands, as can be seen in Figures 10-15. When the power in a given band is analyzed as a percent of the total power, however, different trends appear. Figures 16-21 show that the power changes for delta and theta are not as consistent, and there may be some tendency for delta and theta to be lower in power during Session 4 than Session 2. Alpha as a percent of total power remains greater for Session 4, as it did as an absolute measure. As is seen in Figures 16 and 17, power at both sites tended to increase for alpha between Sessions 2 and 4. In general, power at delta (Figures 18 and 19) and theta (Figures 20 and 21) increased with sleep loss, and then decreased at Session 5.

The matrix represented in Figure 7 reveals that for t-tests of absolute power between Sessions 2 and 4 at Oz, the increase in total power at Pz was significant for the math ($t=3.104$; $p=.0126$) and spatial processing tasks ($t=3.146$; $p=.0104$); while total power at Oz increased for math ($t=5.342$; $p=.0003$), MS 2 ($t=2.980$; $p=.0138$), MS 4 ($t=3.498$; $p=.0057$) and spatial processing ($t=2.340$; $p=.0414$). The increase in alpha during Session 4 at Oz was significant for pre-baseline ($t=3.121$; $p=.0109$), RT 4 ($t=2.889$; $p=.0161$), RT 5 ($t=2.842$; $p=.0175$), math ($t=3.744$; $p=.0038$), and spatial ($t=2.233$; $p=.0496$) tasks. At Pz, alpha increased significantly for RT 4 ($t=3.008$; $p=.0132$), math ($t=6.017$; $p=.0002$), and spatial ($t=2.883$; $p=.0163$) tasks. For the delta band at Oz, math ($t=3.664$; $p=.0044$), MS2 ($t=2.355$; $p=.0403$), and spatial ($t=2.416$;



• = Significant change from session 2 to 4 (p<=.05)

□ = Significant change from session 2 to 5 (p<=.05)

Figure 7. A matrix indicating significance for each of the dependent variables in the study for each STRES battery task for which that measure was collected. Non–intersecting dashed lines imply that no test was performed.

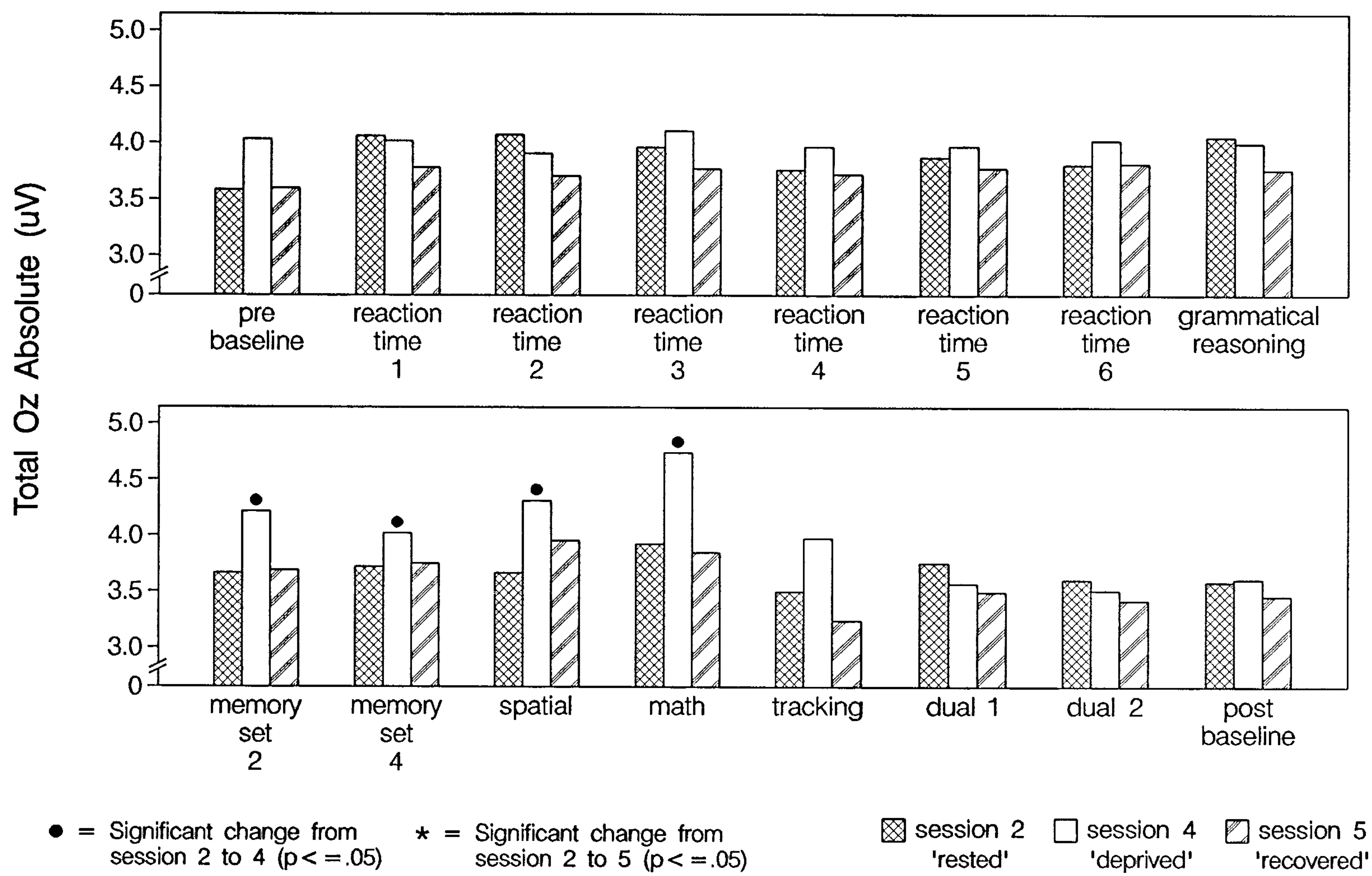


Figure 8. Total absolute EEG power at Oz for baselines and STRES battery tasks over sessions.

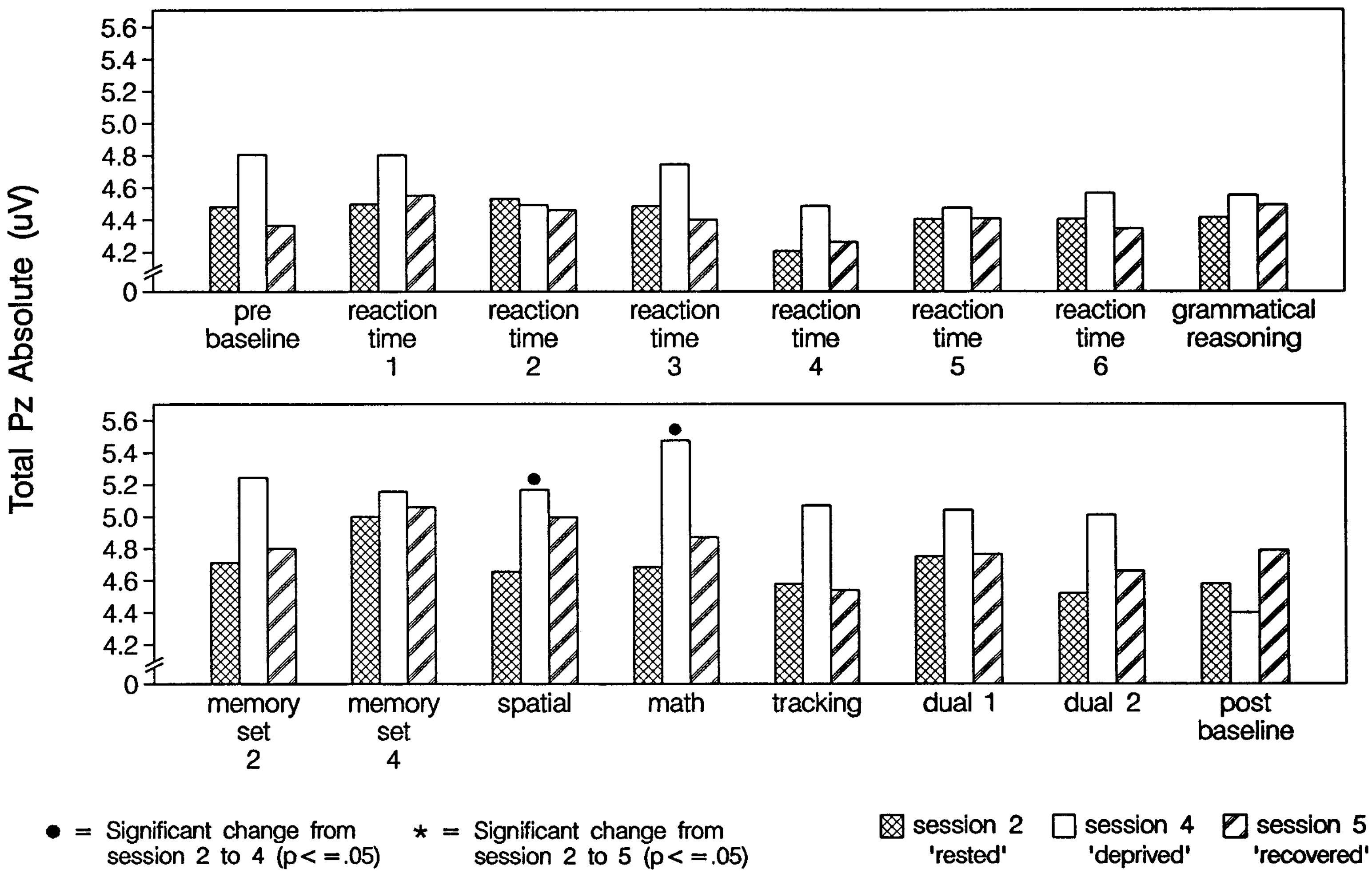


Figure 9. Total absolute EEG power at Pz for baselines and STRES battery tasks over sessions.

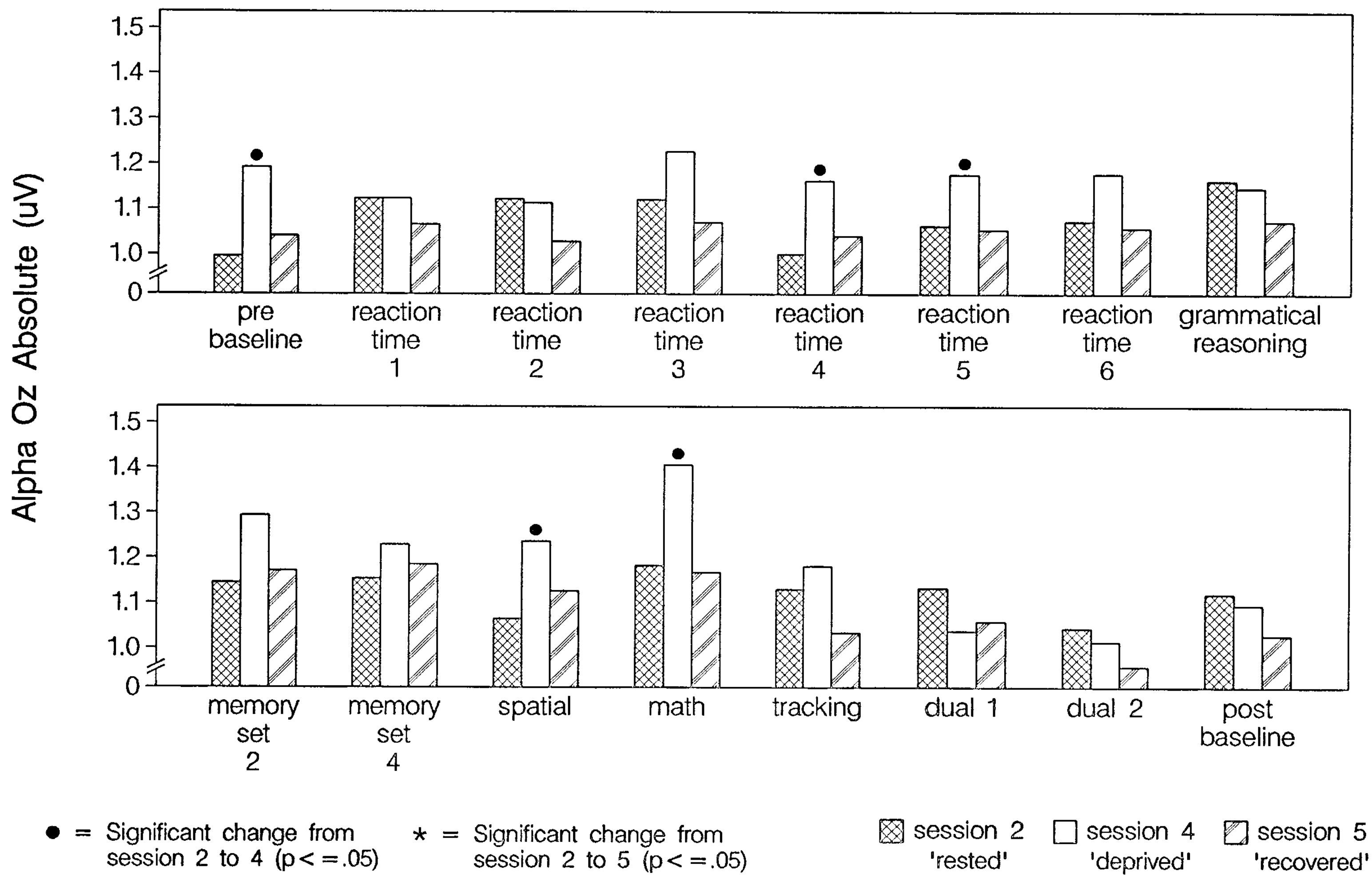


Figure 10. Absolute power at Oz in the alpha EEG band for baselines and STRES battery tasks over sessions.

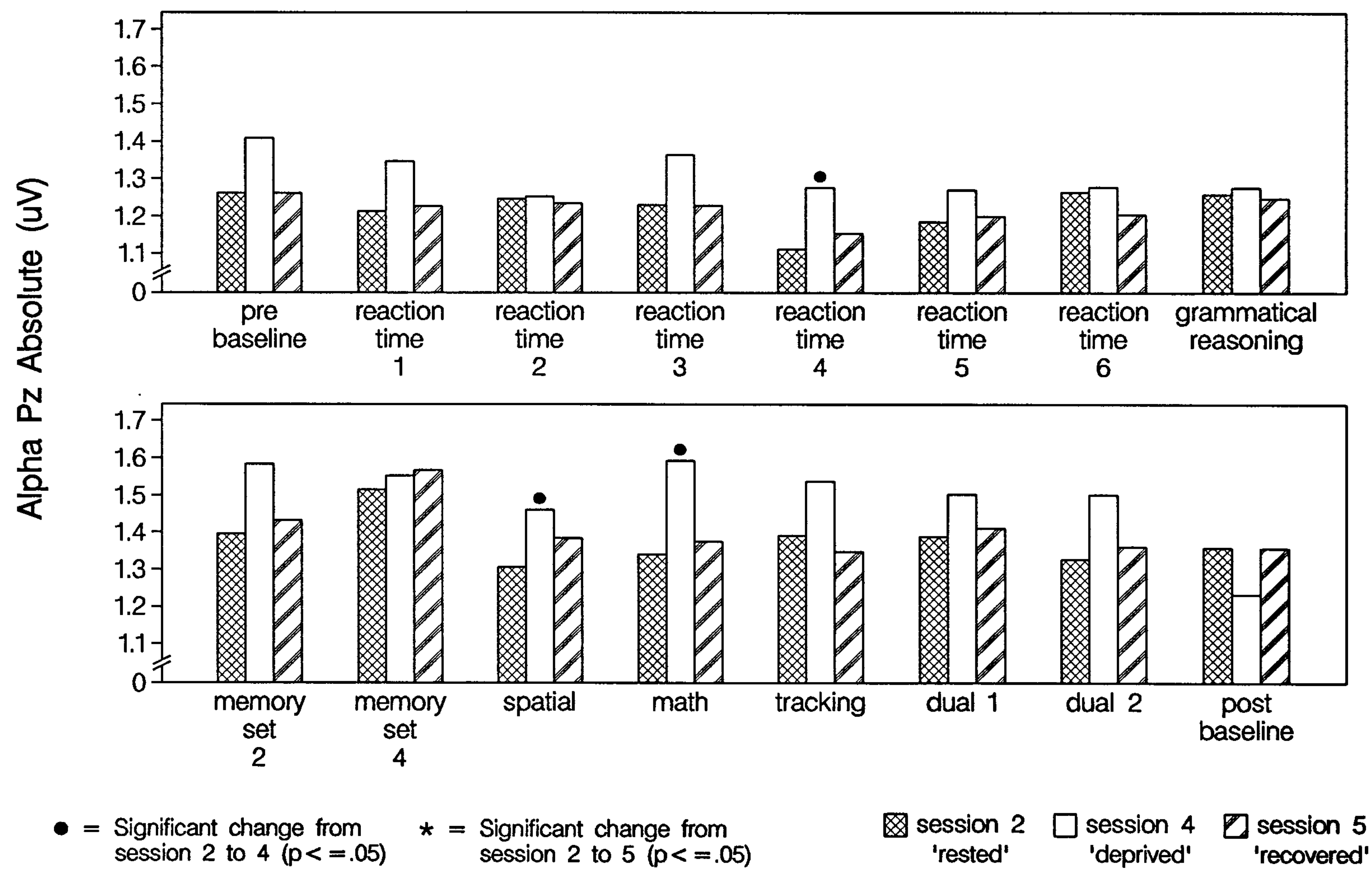


Figure 11. Absolute power at Pz in the alpha EEG band for baselines and STRES battery tasks over sessions.

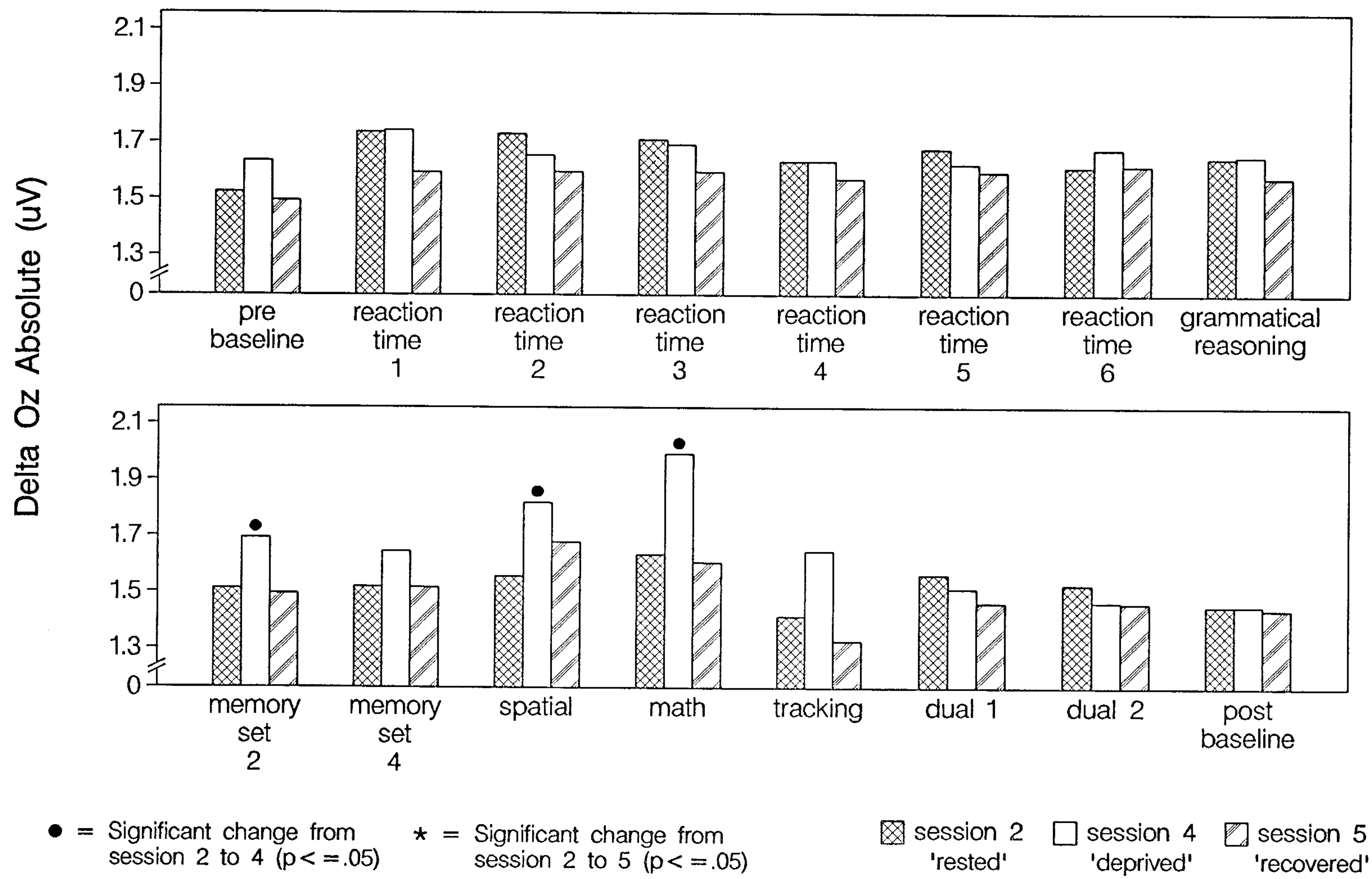


Figure 12. Absolute power at Oz in the delta EEG band for baselines and STRES battery tasks over sessions.

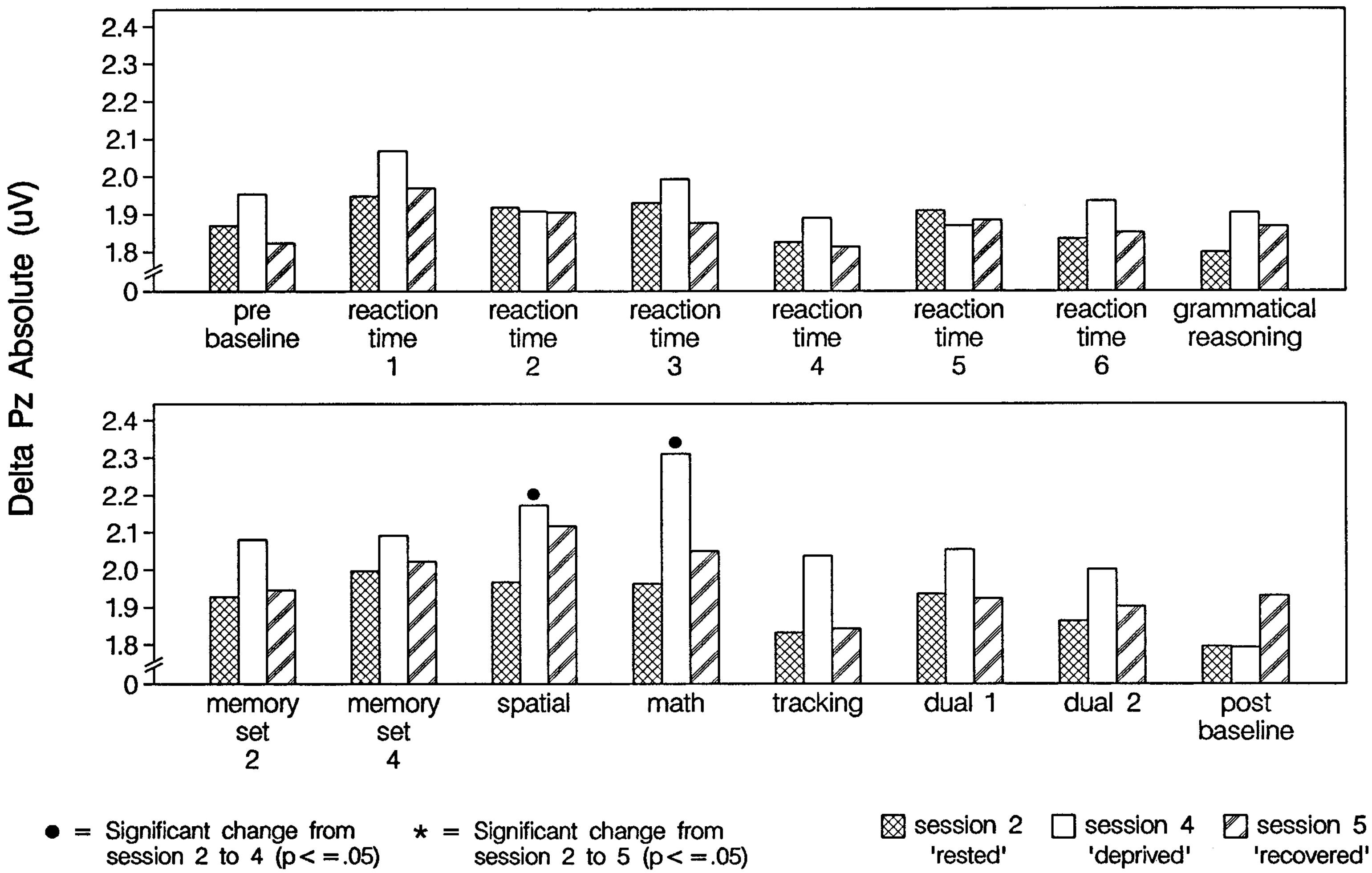


Figure 13. Absolute power at Pz in the delta EEG band for baselines and STRES battery tasks over sessions.

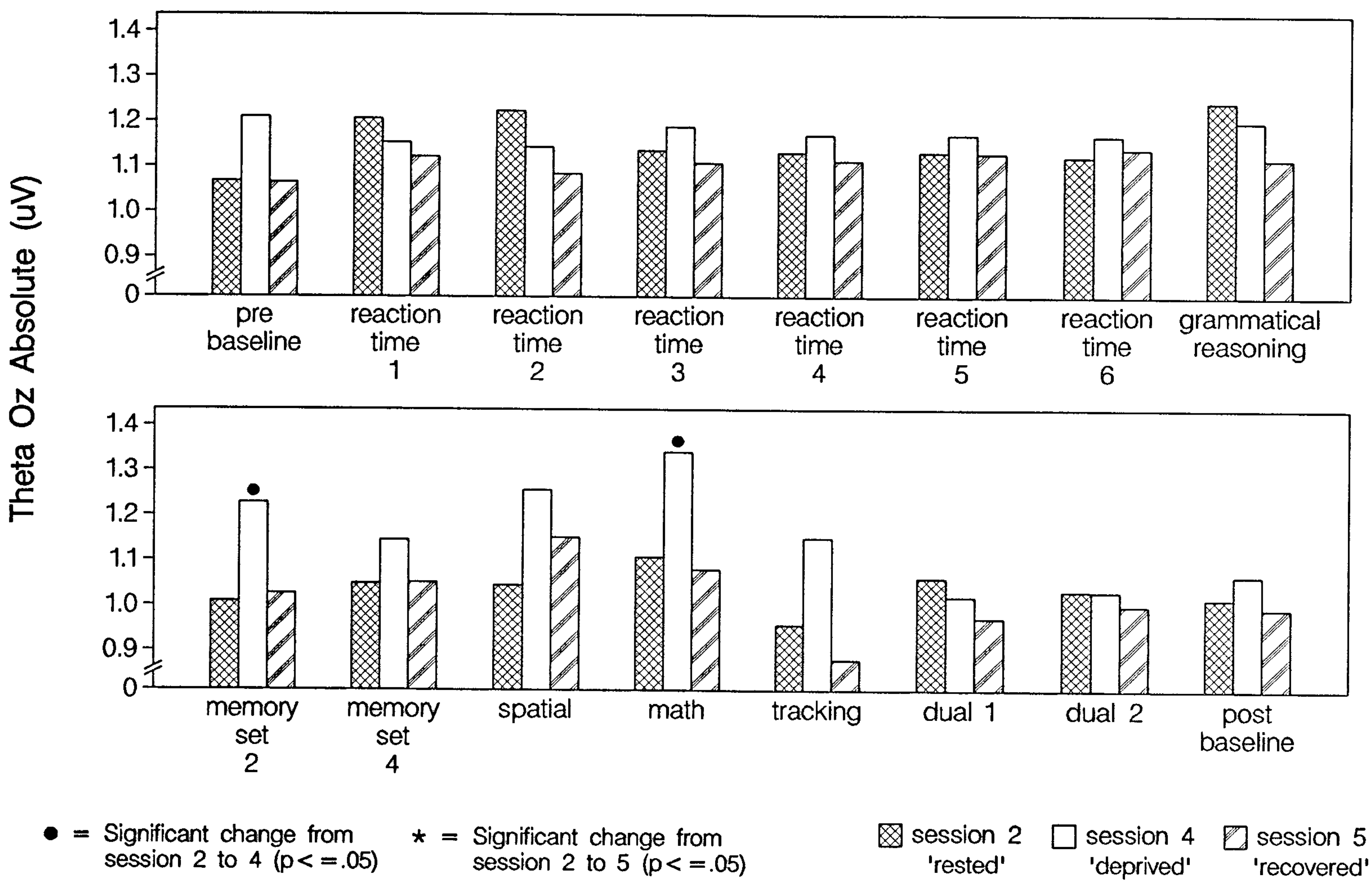


Figure 14. Absolute power at Oz in the theta EEG band for baselines and STRES battery tasks over sessions.

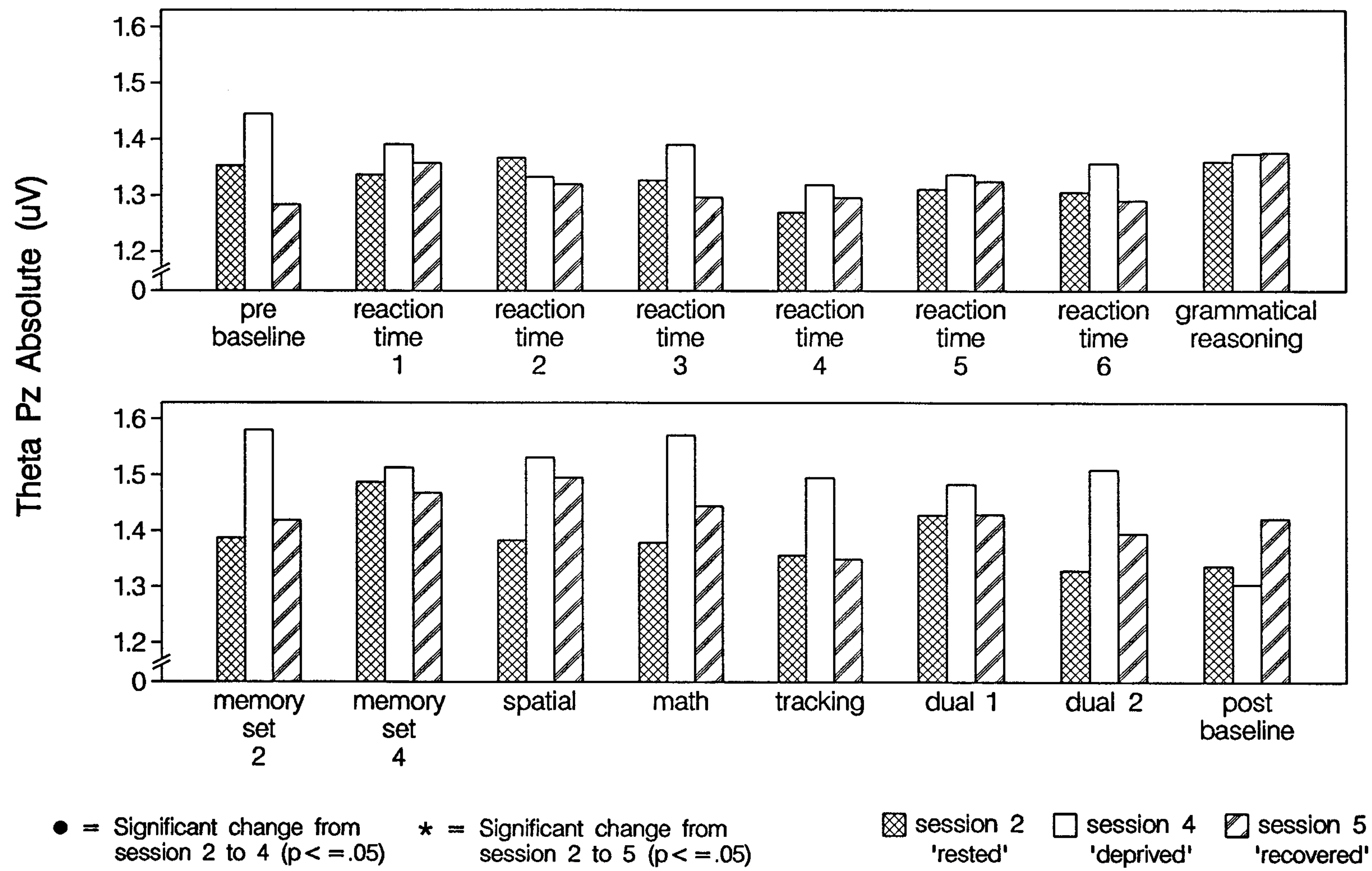


Figure 15. Absolute power at Pz in the theta EEG band for baselines and STRES battery tasks over sessions.

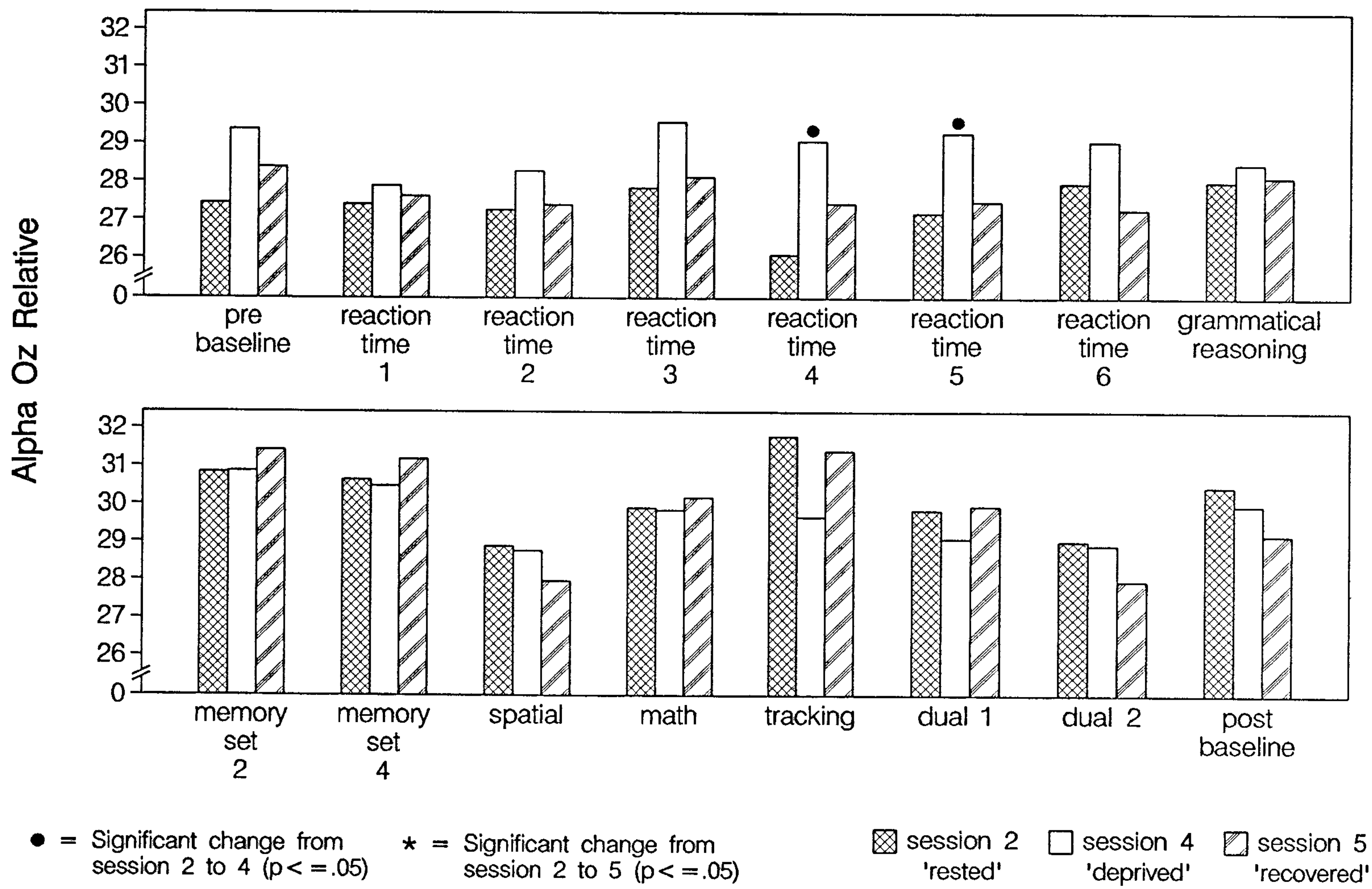


Figure 16. Relative power at Oz in the alpha EEG band for baselines and STRES battery tasks over sessions.

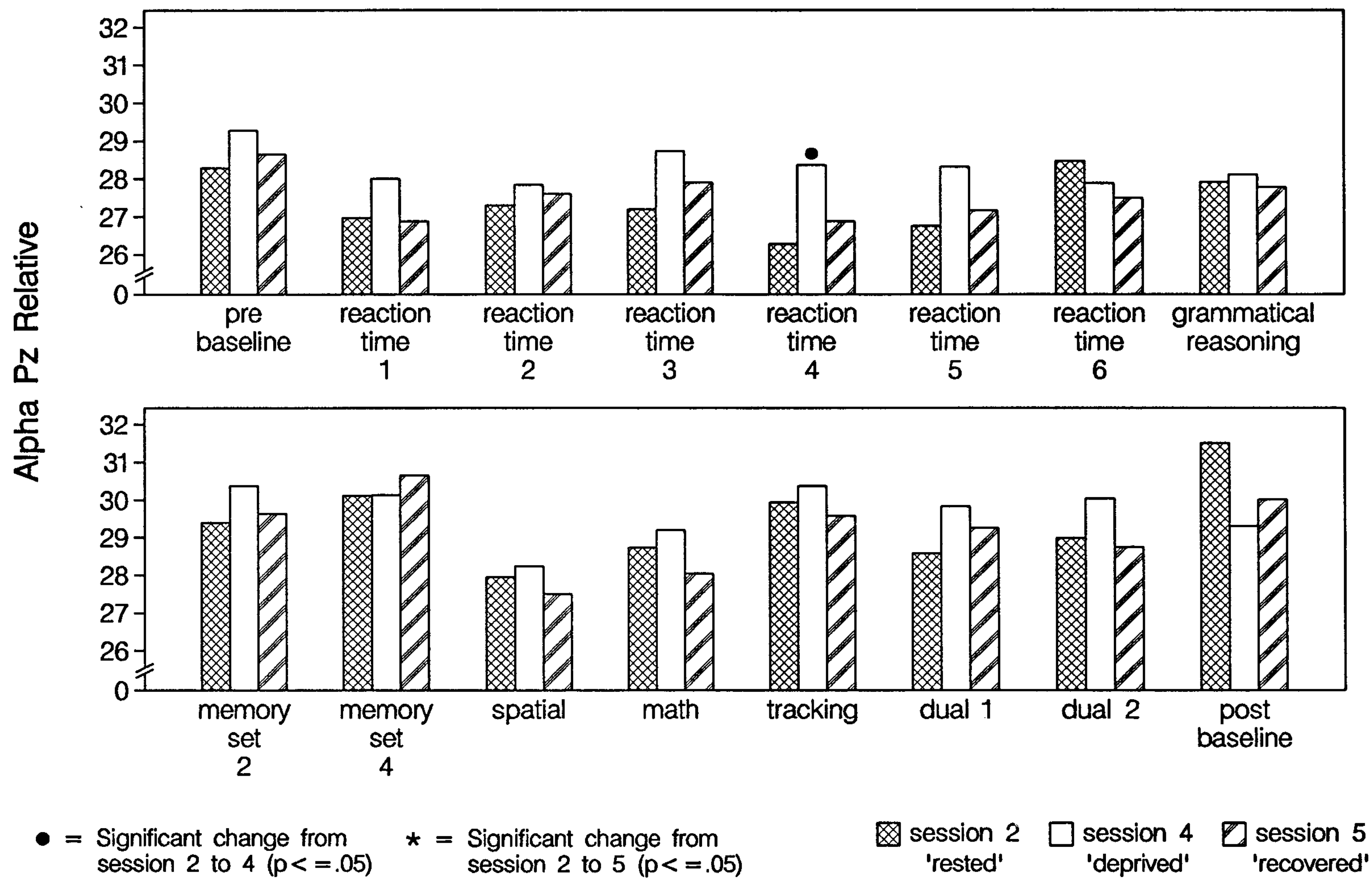


Figure 17. Relative power at Pz in the alpha EEG band for baselines and STRES battery tasks over sessions.

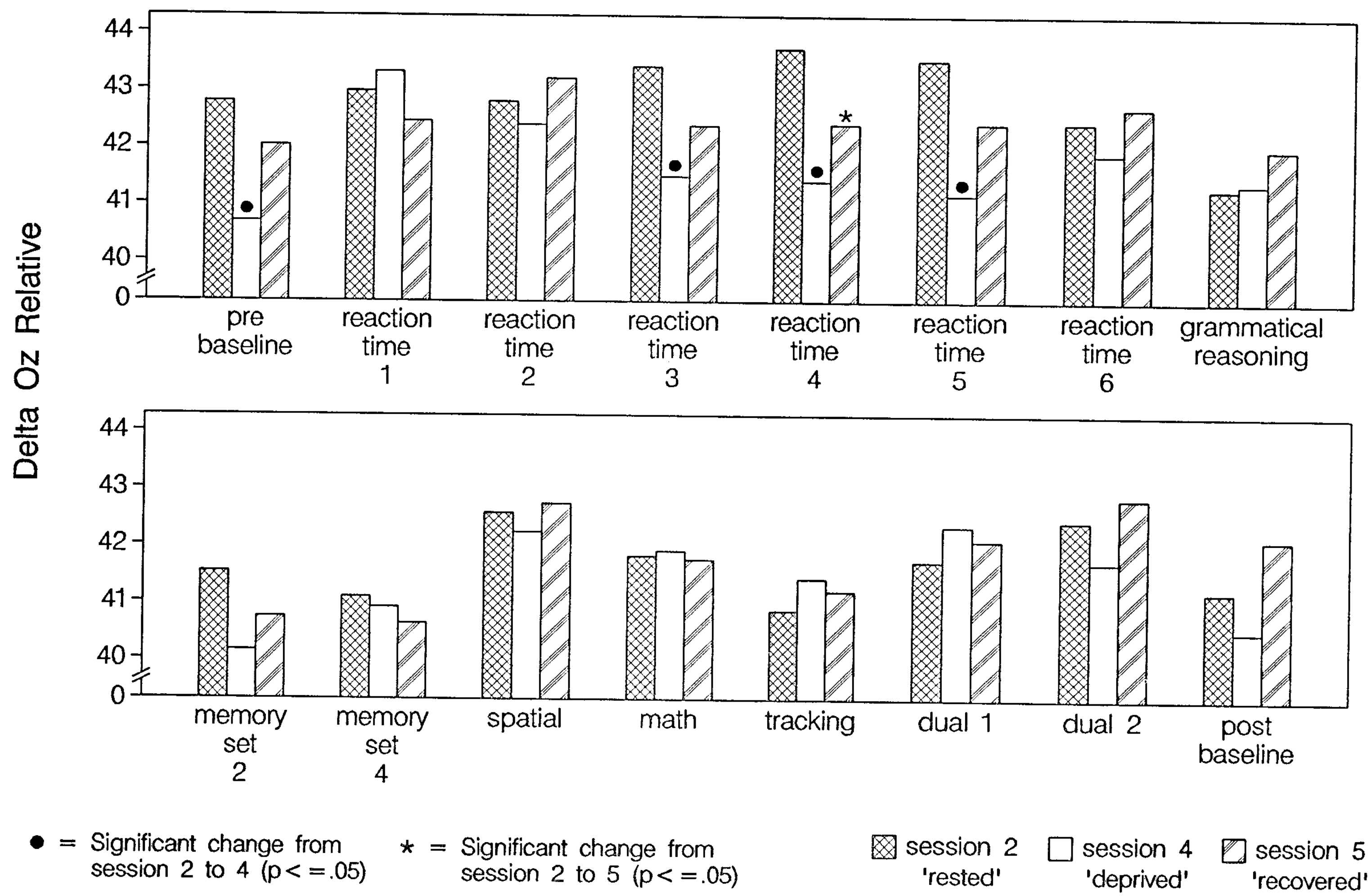


Figure 18. Relative power at Oz in the delta EEG band for baselines and STRES battery tasks over sessions.

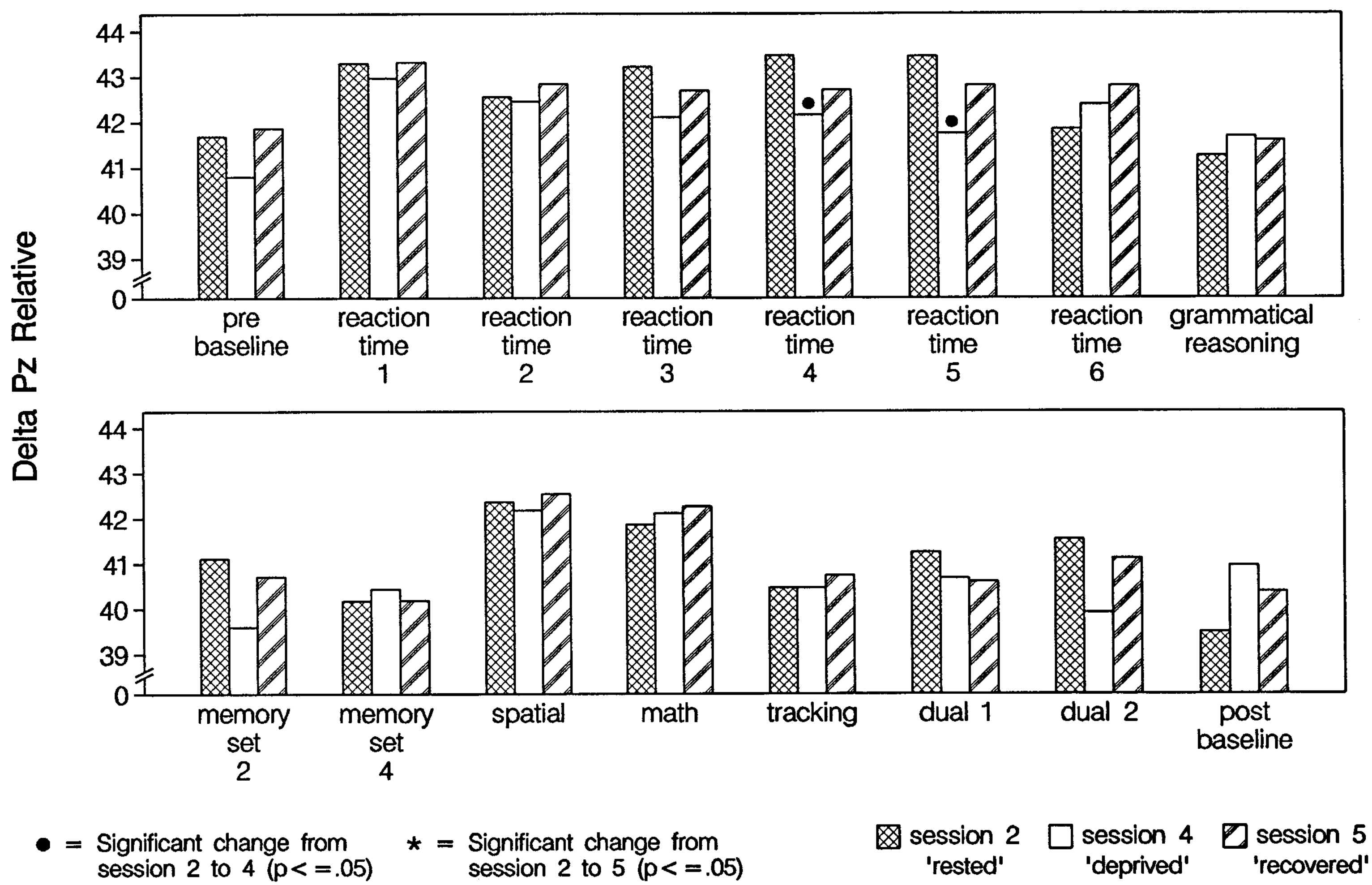
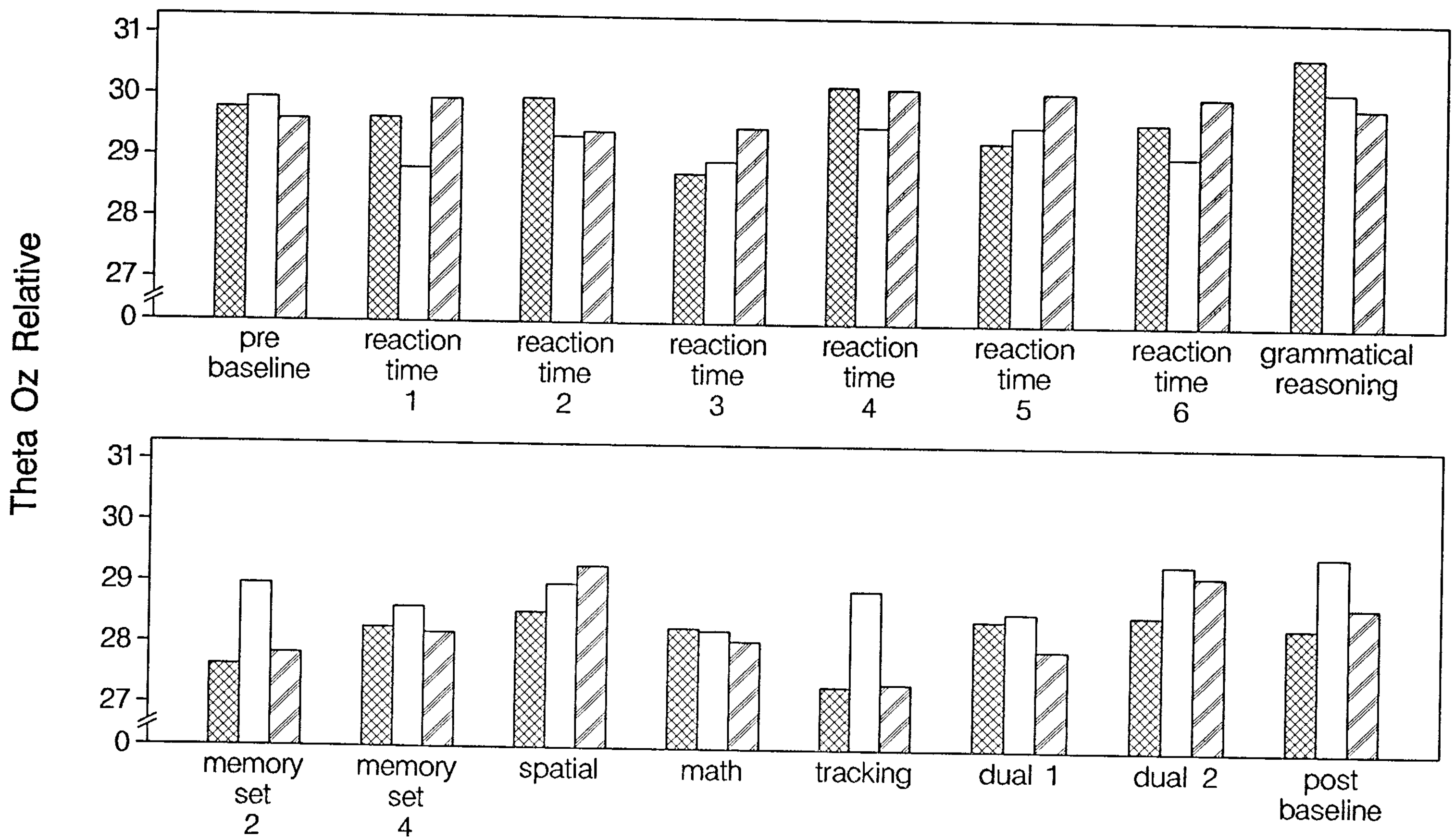


Figure 19. Relative power at Pz in the delta EEG band for baselines and STRES battery tasks over sessions.



● = Significant change from session 2 to 4 (p< =.05) * = Significant change from session 2 to 5 (p< =.05)

session 2 'rested' session 4 'deprived' session 5 'recovered'

Figure 20. Relative power at Oz in the theta EEG band for baselines and STRES battery tasks over sessions.

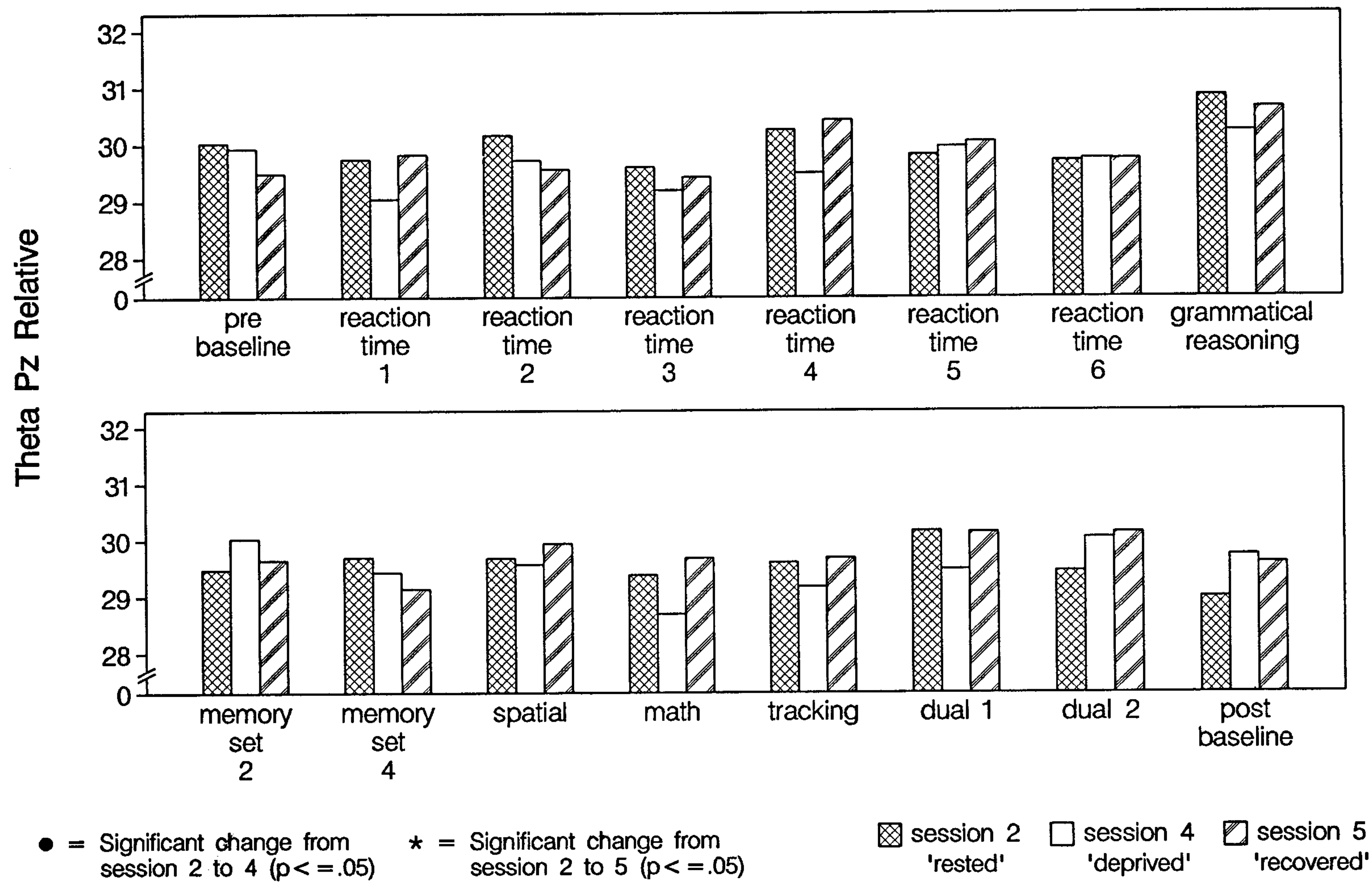


Figure 21. Relative power at Pz in the theta EEG band for baselines and STRES battery tasks over sessions.

p=.0363) tasks all produced greater power during Session 4 compared to Session 2, while delta at Pz showed greater Session 4 power for math (t=4.659; p=.0414) and spatial (t=3.568; p=.0051) tasks. Theta gathered at Oz revealed greater power for Session 4 for math (t=4.659; p=.0009) and MS 2 (t=2.548; p=.0290). For all of these tasks, for all bands, and at both sites, recovery was complete during Session 5.

When relative power was analyzed, there was a significant increase in alpha power at Pz for RT 4 (t=2.304; p=.0440) and at Oz for RT 4 and RT 5 (t=2.347; p=0.408; t=2.565; p=.0281, respectively). Relative delta decreased between Sessions 2 and 4 for RT 4 and RT 5 (t=-2.341; p=.0413; t=-2.339; p=.0414, respectively) at Pz, and at Oz, for tasks RT 3, RT 4, and RT 5 (t=-2.693; p=.0226; t=-3.370; p=.0071; t=-3.402; p=.0067, respectively). There were no significant theta differences in relative power over sessions.

Between Sessions 2 and 5, the only relative power difference was delta at Oz, for RT 4 (t=-2.863; p=.0230).

Evoked Potentials

The analysis and plots of amplitude and latency for the three EP components did not produce a clear picture of amplitude or latency effects as a function of sleep loss. The matrix in Figure 7 indicates which of the experimental task/EP variable differences reached significance. For N1, Oz amplitude during RT 2 was significantly higher for Session 4 than it was for Session 2 (t=2.309; p=.0436). Pz amplitude was lower for MS 4 at Session 4 compared to Session 2 (t=2.774; p=.0275). Latencies at Oz were greater during Session 4 during both dual task conditions (Dual Tasks 1, t=2.281; p=.0485; Dual Tasks 2, t=2.372; p=.0418, respectively). For this component, there were no significant effects of latency at Pz.

For P2, the only significant difference between Sessions 2 and 4 was the greater latency recorded at Pz during Session 4's math task (t=2.486; p=.0347).

P3's amplitude was greater during Session 4 for RT 3, as recorded at Oz (t=2.528; p=.0300). Also at Oz, latency was greater during Session 2 for RT 4 (t=-2.448; p=.0344). Pz latency also decreased during Session 4 for during spatial processing (t=-2.638; p=.0248).

The task/EP-measure combinations for which recovery was not complete can be seen in Figure 7. The only latency which did not show full recovery with a night's sleep was N1 at Oz, for RT 3 (t=5.369; p=.0003), with a longer latency at Session 5 than Session 2. Amplitudes which differed between Sessions 2 and 5 were limited to N1 at Pz, for the spatial task (t=-2410; p=.0393) with a greater amplitude at Session 5 than Session 2; P3 showing a greater amplitude at Session 5 at Pz, for RT 1 (t=2.652; p=.0242), and P3, at Oz, showing increased amplitude at Session 5 compared to Session 2 for grammatical reasoning (t=2.357; p=0.401).

Eye Blink Measures

Figures 22-24 plot eye blink measures over sessions. Blink rate in Figure 22 shows consistent increases between Sessions 2 and 4, and then decreases for Session 5. Figure 23 indicates that blink duration increases with sleep loss and then decreases after a night's recovery sleep. Blink amplitude results in Figure 24 show no consistent change and no results were significant for any of the experimental tasks.

T-tests indicated that the increase in blink rate from Session 2 to Session 4 was significant for RT 1 (t=2.996; p=.0134), RT 6 (t=2.745; p=.0206), math (t=2.396; p=.0376), and tracking (t=3.574; p=.0051). Blink duration was significantly greater during Session 4 for RT 1 (t=2.733; p=.0467), RT 3 (t=3.590; p=.0049), MS 4 (t=2.557; p=.0285), and tracking (t=3.447; p=.00063). Figure 7 indicates that all eye measures and tasks showed recovery except for eye blink rate at RT 1 (t=2.733; p=.0211), RT 4 (t=3.040; p=.0125), RT 6 (t=2.422; p=.0359), and tracking (t=3.447; p=.0396), where there were differences between Session 2 and Session 5.

Heart Rate Measures

Figure 25 plots heart rate as it decreased between Sessions 2 and 4, and increased a

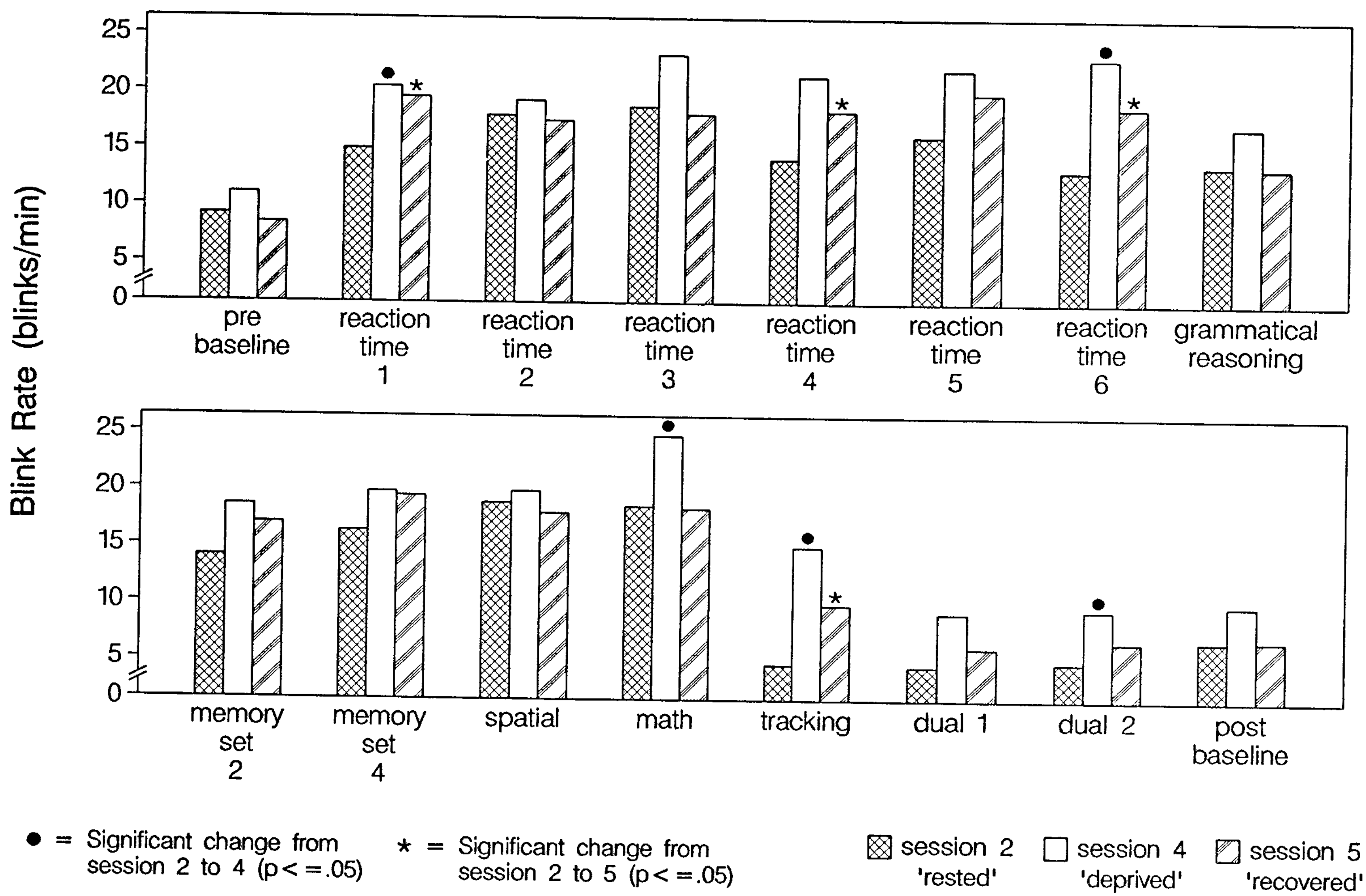


Figure 22. Mean blink rate for baselines and STRES battery tasks over sessions.

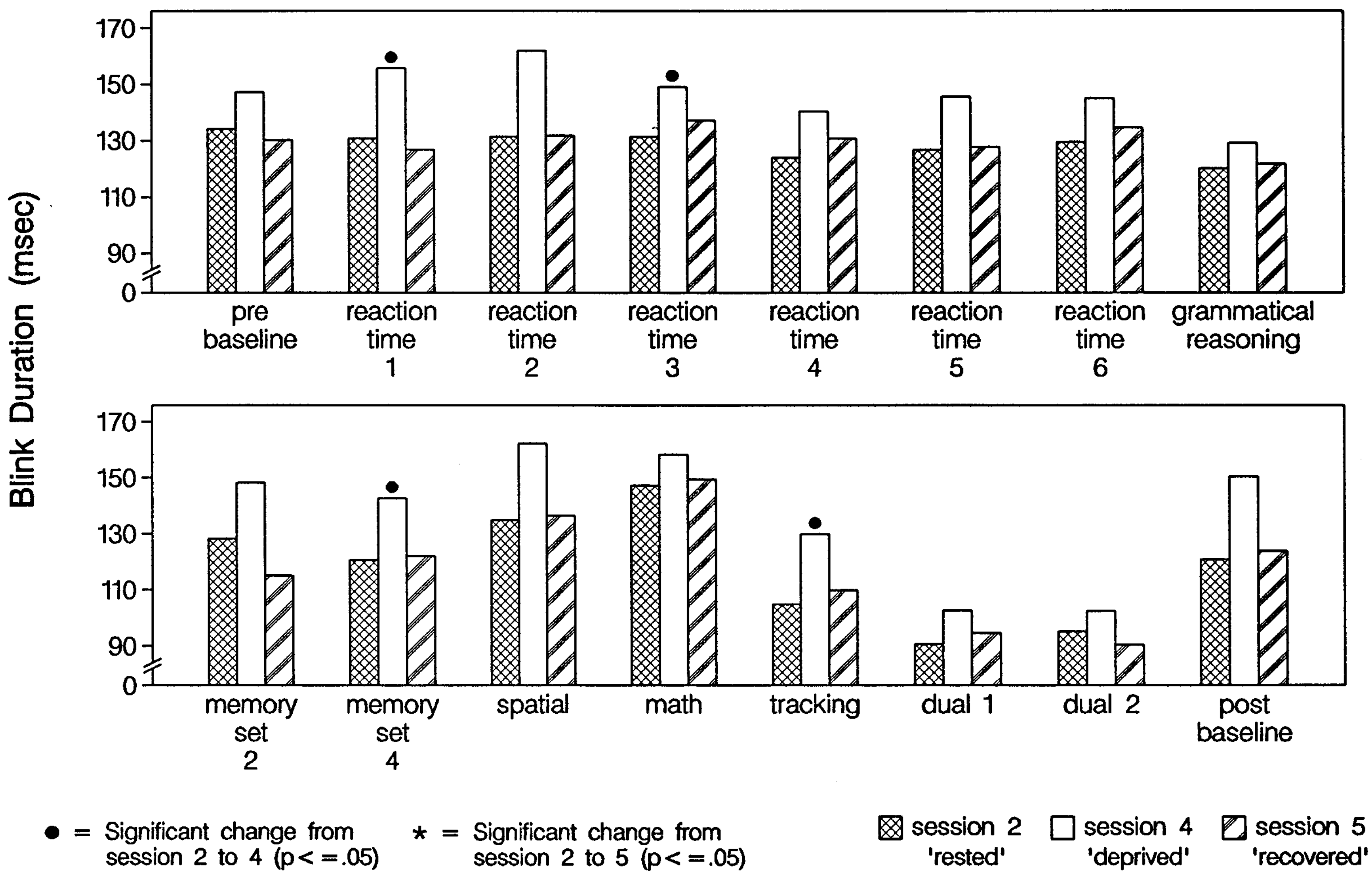


Figure 23. Mean blink duration for baselines and STRES battery tasks over sessions.

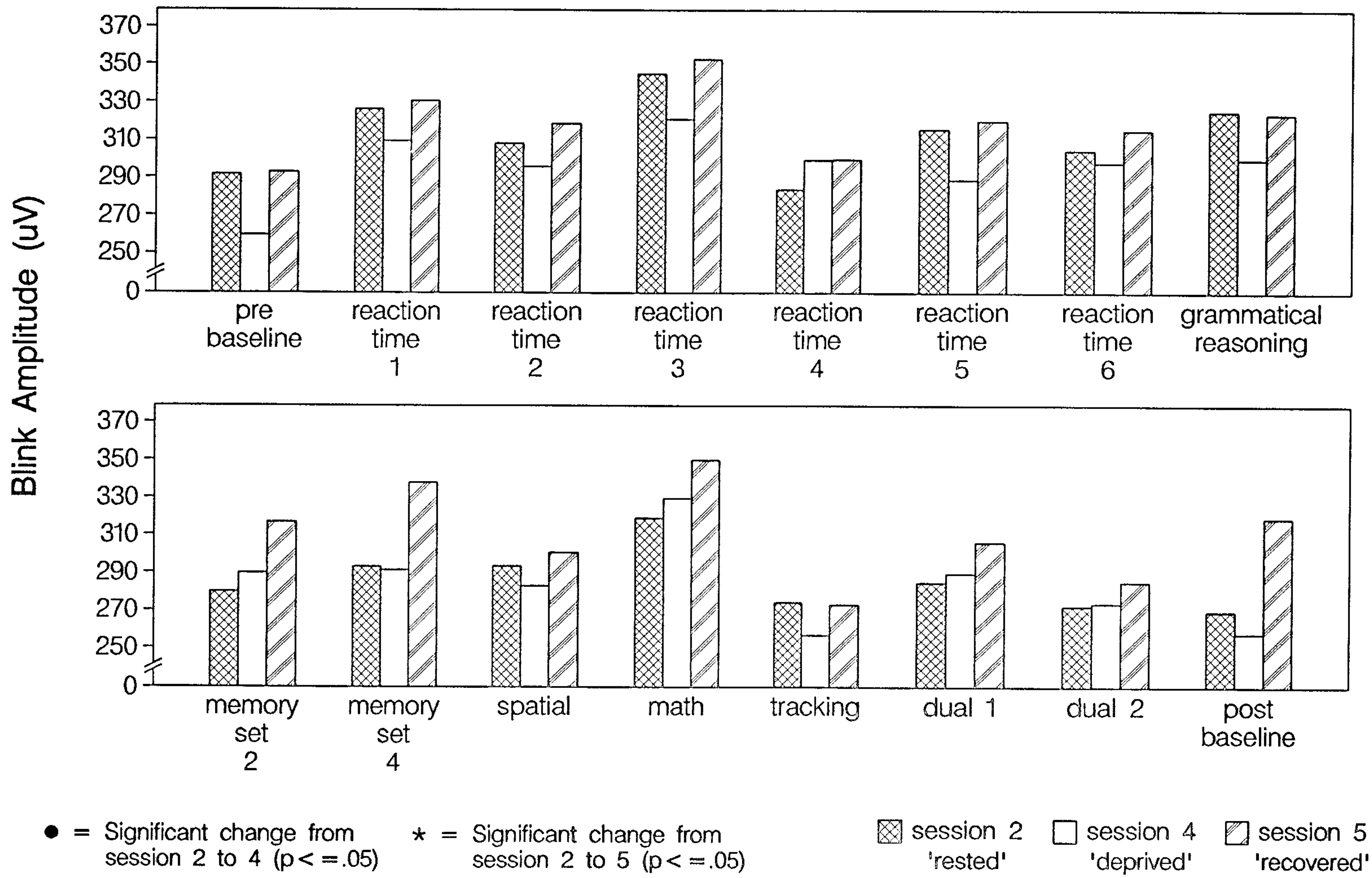


Figure 24. Mean blink amplitude for baselines and STRES battery tasks over sessions.

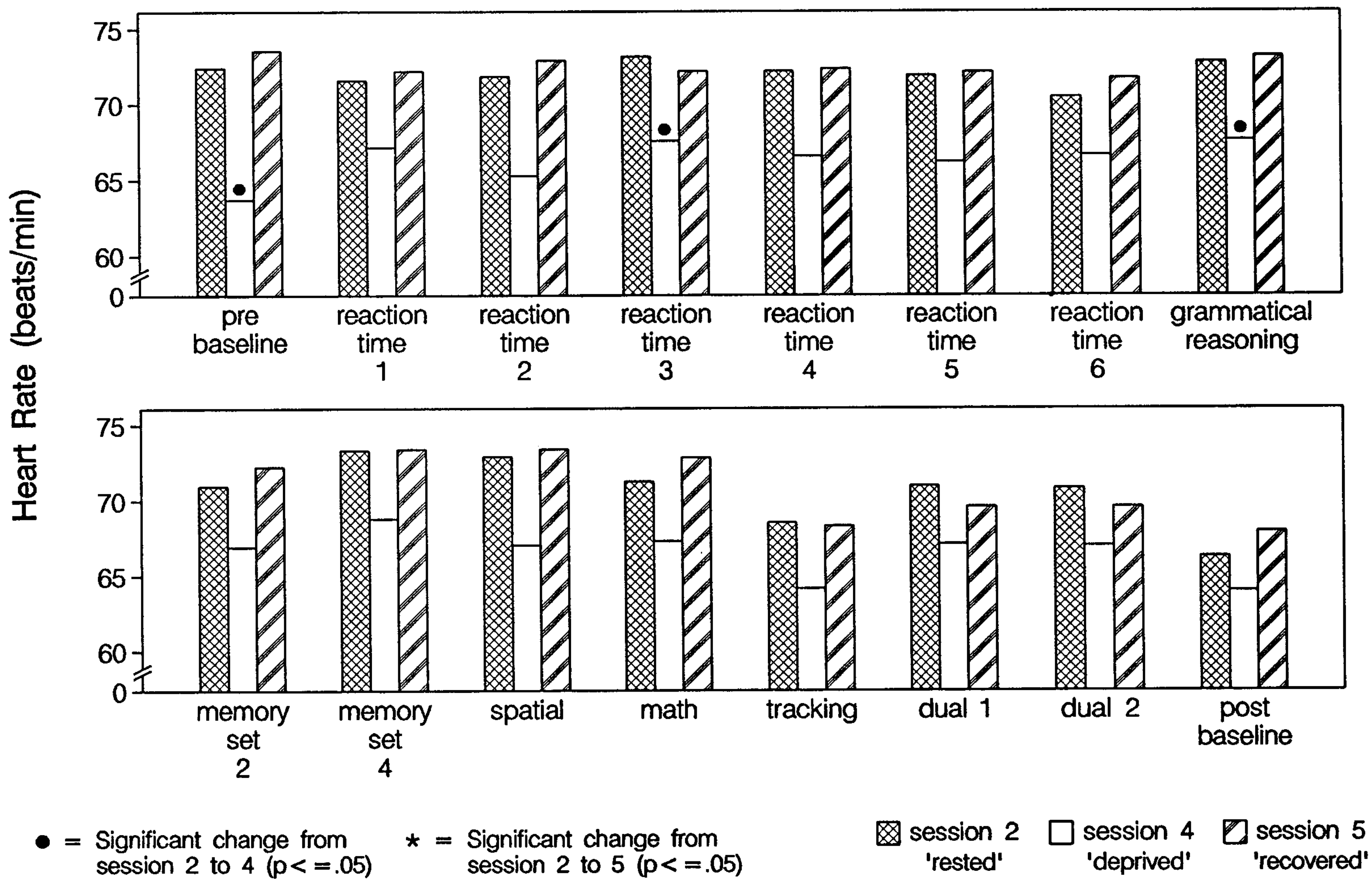


Figure 25. Mean heart rate for baselines and STRES battery tasks over sessions.

increased at Session 5. Significant effects can be seen in Figure 7; t-tests revealed that between Sessions 2 and 4, rate decreased significantly for pre-baseline ($t=3.146$; $p=.0104$), RT 3 ($t=3.358$; $p=.0401$) and the grammatical task ($t=2.276$; $p=.0461$). There were no significant differences comparing Sessions 2 and 5, as can be seen in Figure 7.

Heart rate variability is plotted in Figures 26 (high) and 27 (medium). Variability consistently increased between Sessions 2 and 4, and decreased at Session 5. Figure 7 shows that between Sessions 2 and 4, significant changes were seen for HRV-high for pre-baseline ($t=2.962$; $p=.0142$), RT2, ($t=2.317$; $p=.0430$), RT3 ($t=3.370$; $p=.0071$), RT 4($t=2.912$; $p=.0155$), RT 5 ($t=2.477$; $p=.0327$), RT6 ($t=2.492$; $p=.0319$), math ($t=2.487$; $p=.0322$), MS 2 ($t=2.632$; $p=.0251$), MS 4 ($t=2.777$; $p=.0196$), spatial ($t=3.489$; $p=.0058$), tracking ($t=2.120$; $p=.0600$), and Dual Tasks 1 ($t=2.321$; $p=.0427$). There were no significant changes between Sessions 2 and 5 for the high band value of HRV, as can be seen in Figure 7.

For HRV-medium, Session 2 to 4 changes were significant for RT 2 ($t=2.434$; $p=.0352$), RT 3 ($t=2.381$; $p=.0385$), RT 6 ($t=2.991$; $p=.0135$), math ($t=3.083$; $p=.0116$), MS 2 ($t=2.734$; $p=.0210$), MS 4 ($t=2.744$; $p=.0207$), and Dual Tasks 1 ($t=3.784$; $p=.0036$). RT 5 differed significantly ($t=-2.270$; $p=.0466$) between Sessions 2 and 5, as can be seen in Figure 7.

Subjective Data over Sessions

Composite scores on the NASA-TLX were higher at Session 4 than at Session 2, and decreased during Session 5, as can be seen in Figure 28. The results of t-tests between Sessions 2 and 4 which were significant are indicated in Figure 7. Tasks for which the Session 2 to 4 difference was significant were RT 3 ($t=3.263$; $p=.0085$), RT 4 ($t=3.690$; $p=.0042$), RT 6 ($t=3.718$; $p=.0040$), MS 4 ($t=2.493$; $p=.0318$), spatial processing ($t=2.458$; $p=.0338$), and tracking ($t=4.325$; $p=.0015$). Figure 7 shows a significant difference between Sessions 2 and 5 for Dual Tasks 1 ($t=-3.982$; $p=.0026$).

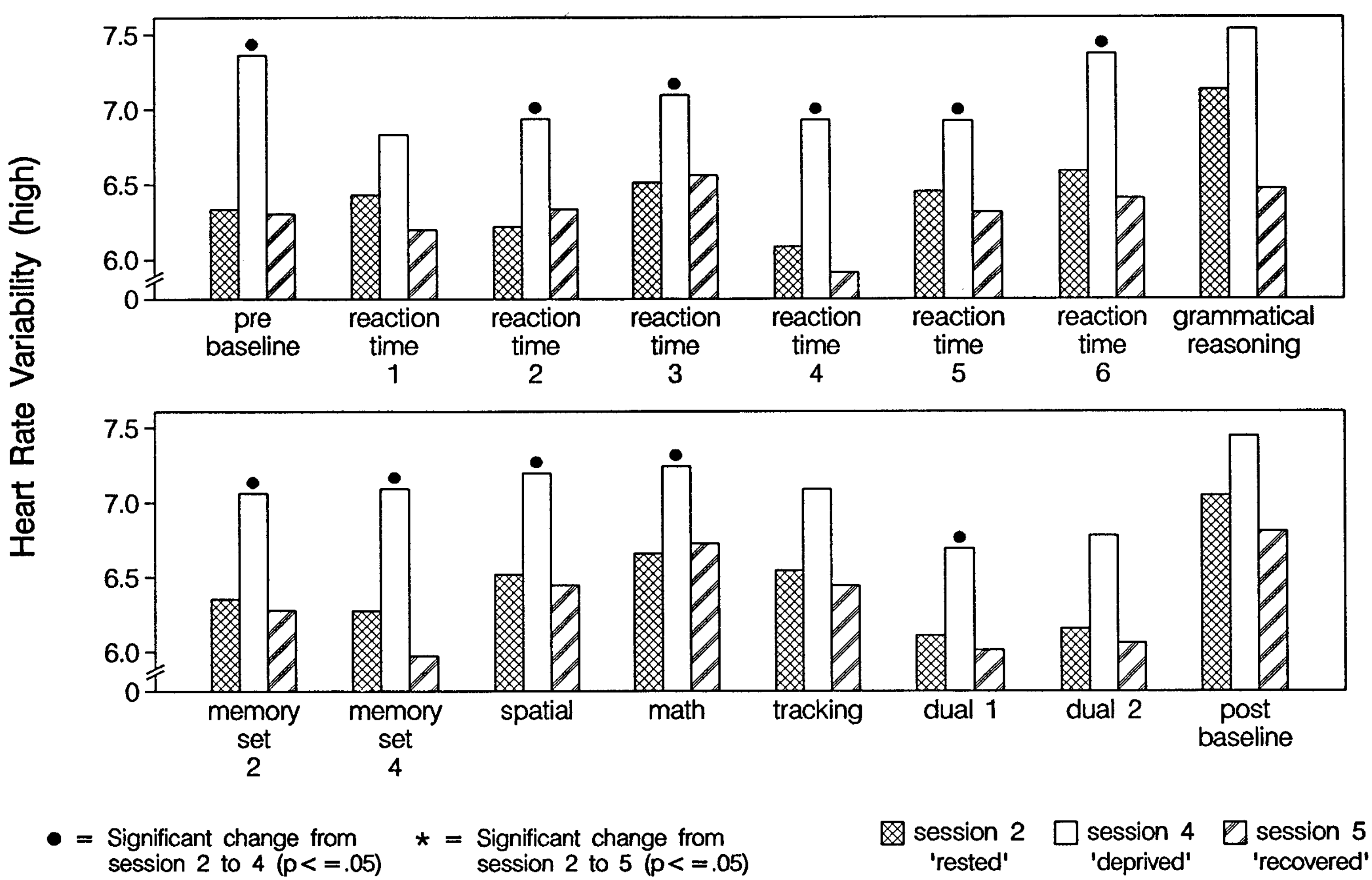


Figure 26. Mean heart rate variability (high 0.15–0.40 Hz) for baselines and STRES battery tasks over sessions.

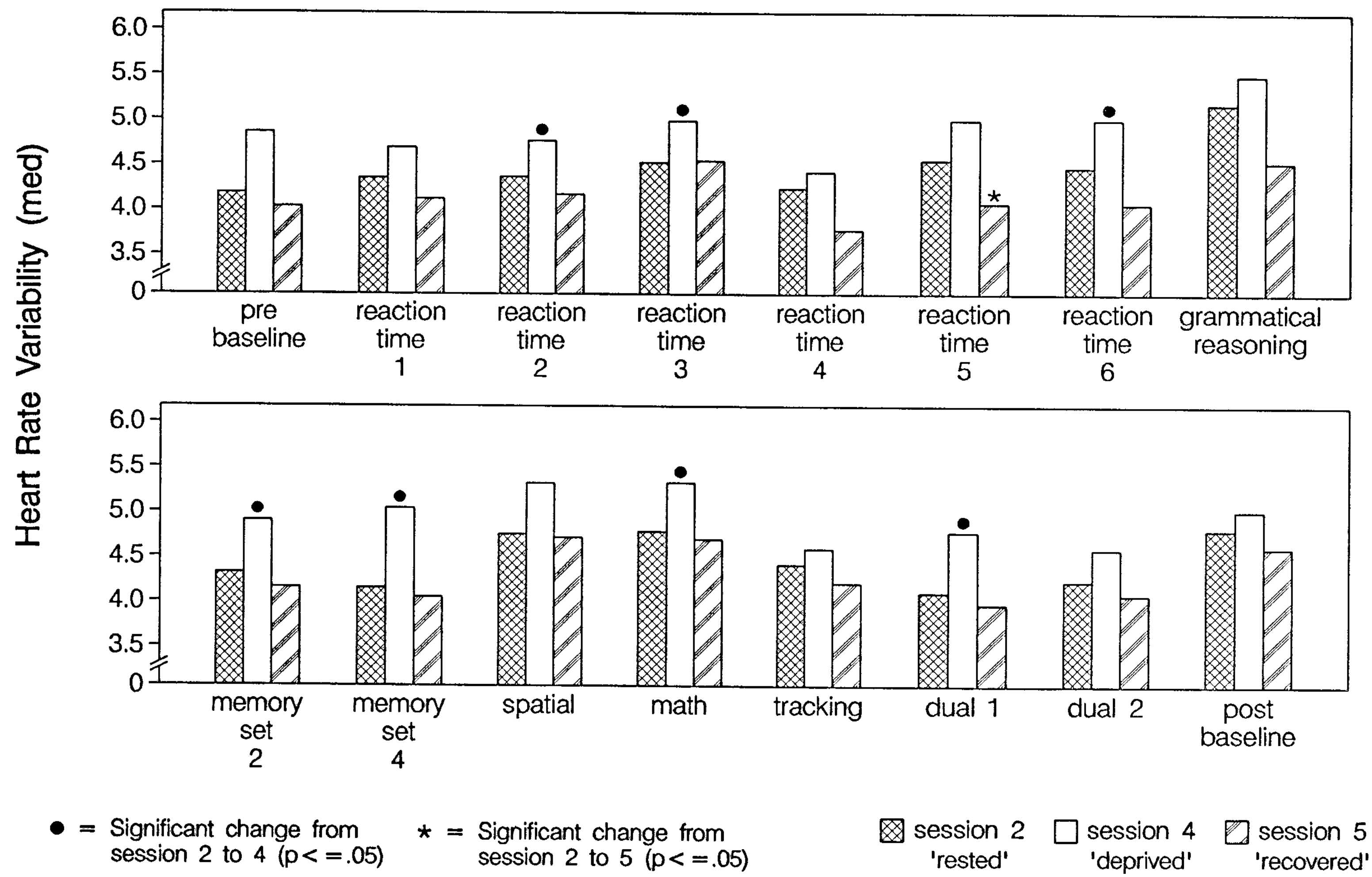


Figure 27. Mean heart rate variability (medium 0.06–0.14 Hz) for baselines and STRES battery tasks over sessions.

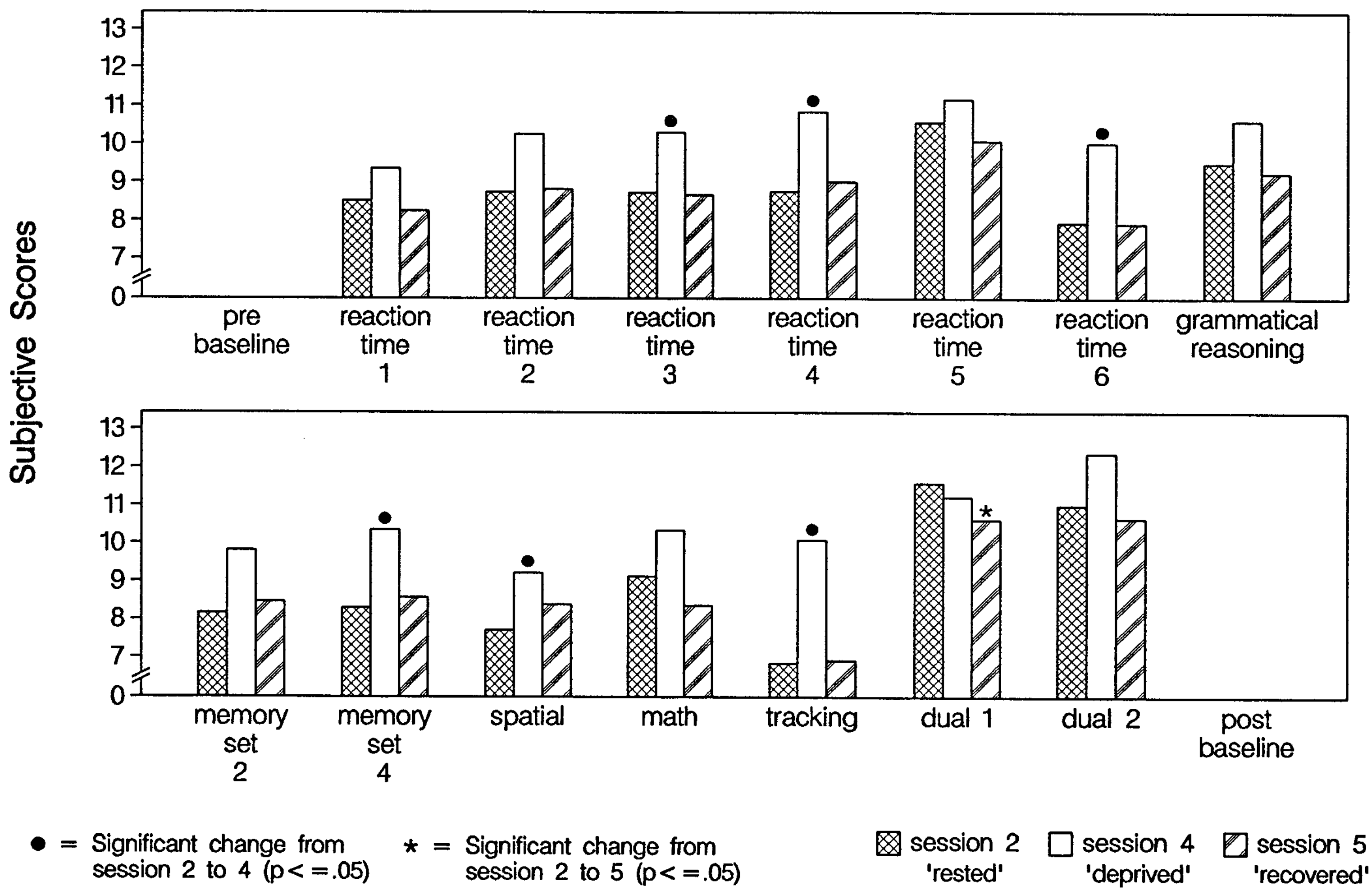


Figure 28. Mean subjective (NASA–TLX) scores for STRES battery tasks over sessions.

Between Tasks Comparisons

In addition to the discussion about the affects of sleep loss, this study helps answer a more basic question about the sensitivity of certain physiological measures to the cognitive demands of the different STRES Battery tasks. Measures within Session 2, with no sleep loss influence, indicate the sensitivity of several physiological measures to task differences. Examination of the different physiological outcomes between STRES Battery tasks in rested, practiced subjects can tell us about the relative task requirements and how they affect physiological measures.

Figure 29 plots heart rate during Session 2 as a function of each STRES Battery task. The matrix indicates which tasks differed significantly from one another along this measure. Post-baseline heart rate was significantly lower than heart rate during several tasks, and heart rate during tracking was also lower than for several other tasks.

Heart rate variability at the high band is plotted in Figure 30; post-baseline variability showed the greatest number of between-task differences. RT 4 and the dual tasks were associated with significantly lower HRV than several other tasks. Although HRV appears high during the grammatical reasoning task, the between-subject variability was great enough to prevent many significant between-task findings. Heart rate variability with the medium band for Session 2 is illustrated in Figure 31; again, the higher levels of variability during post-baseline accounted for several of the significant task comparisons. The reduced level of HRV at RT 4 resulted in significant differences between that task and the grammatical ($t=2.252$, $p=.0480$), spatial $t=2.392$, $p=.0378$), and math ($t=2.557$, $p=.0285$) tasks, and the post-baseline ($t=2.394$, $p=.0377$). The Dual 1 and Dual 2 tasks were also associated with lower HRV.

Blink rate within Session 2 shows greatly reduced rates for the tracking tasks (under single and dual-task conditions) and the post-baseline, compared to all the other STRES Battery tasks. The math and spatial tasks showed some evidence of

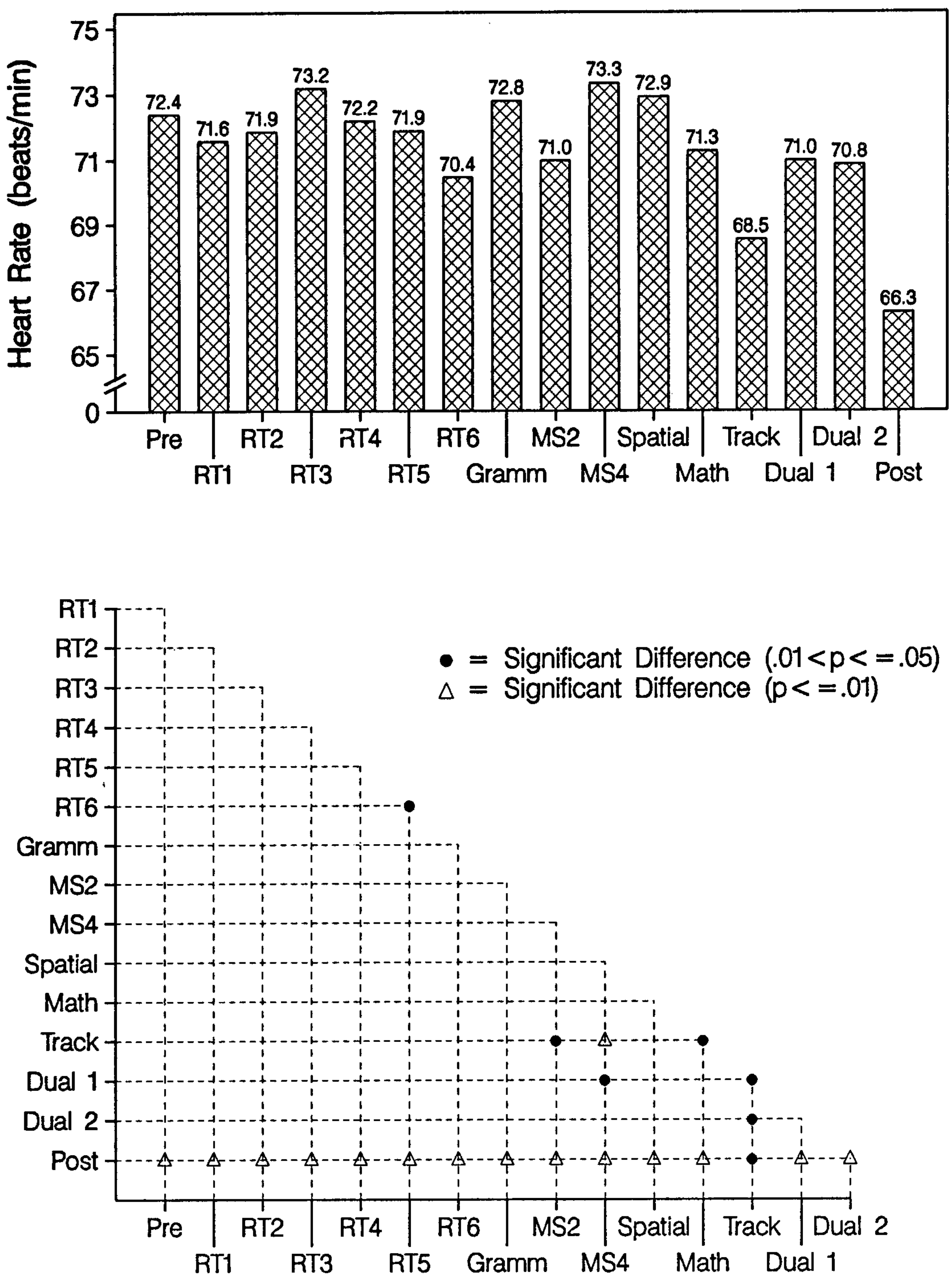


Figure 29. Top: Mean heart rate for baselines and STRES battery tasks for Session 2. Bottom: Matrix of significance of between task comparisons.

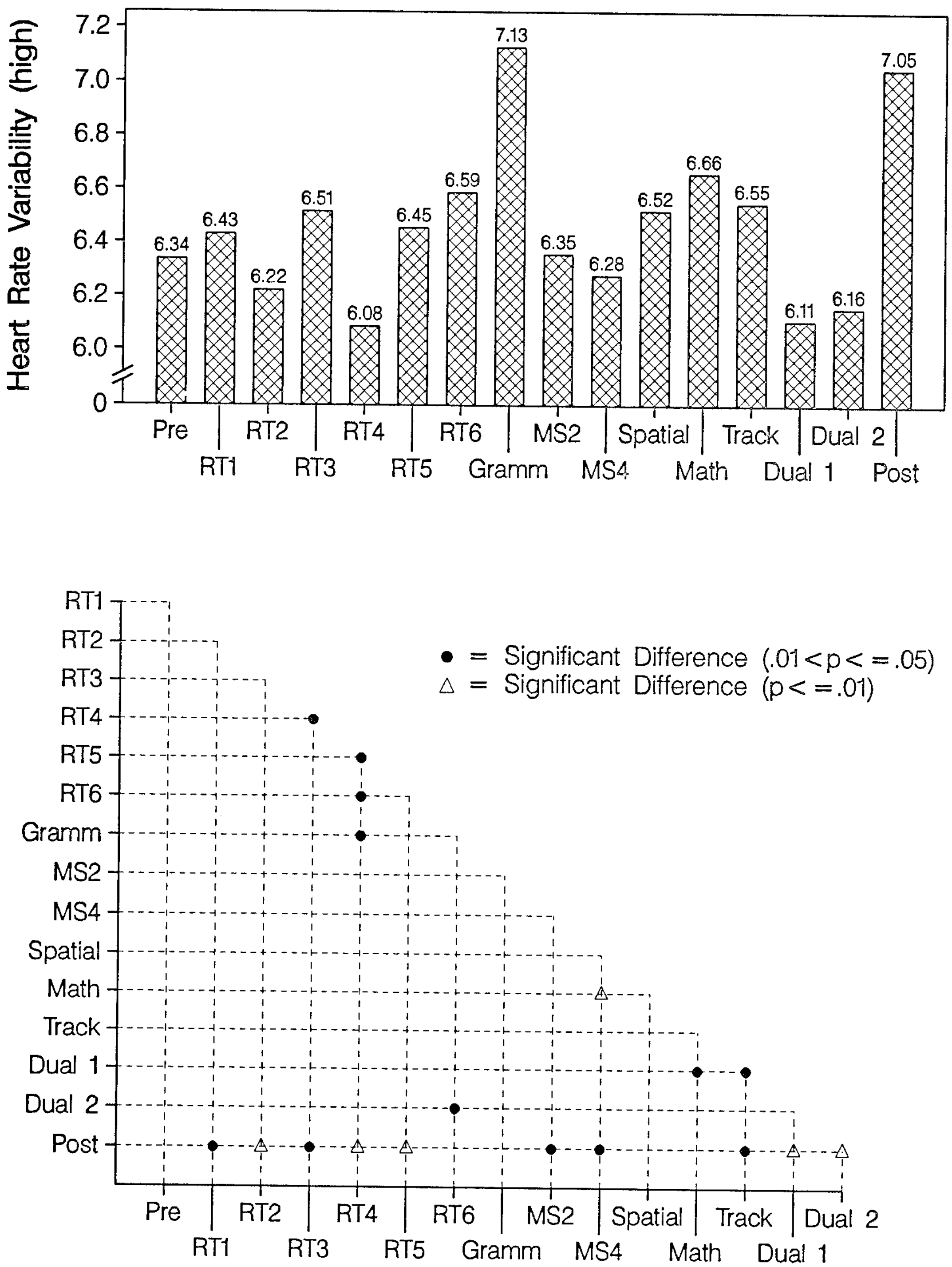


Figure 30. Top: Mean heart rate variability (high 0.15–0.40 Hz) for baselines and STRES battery tasks for Session 2.

Bottom: Matrix of significance of between task comparisons.

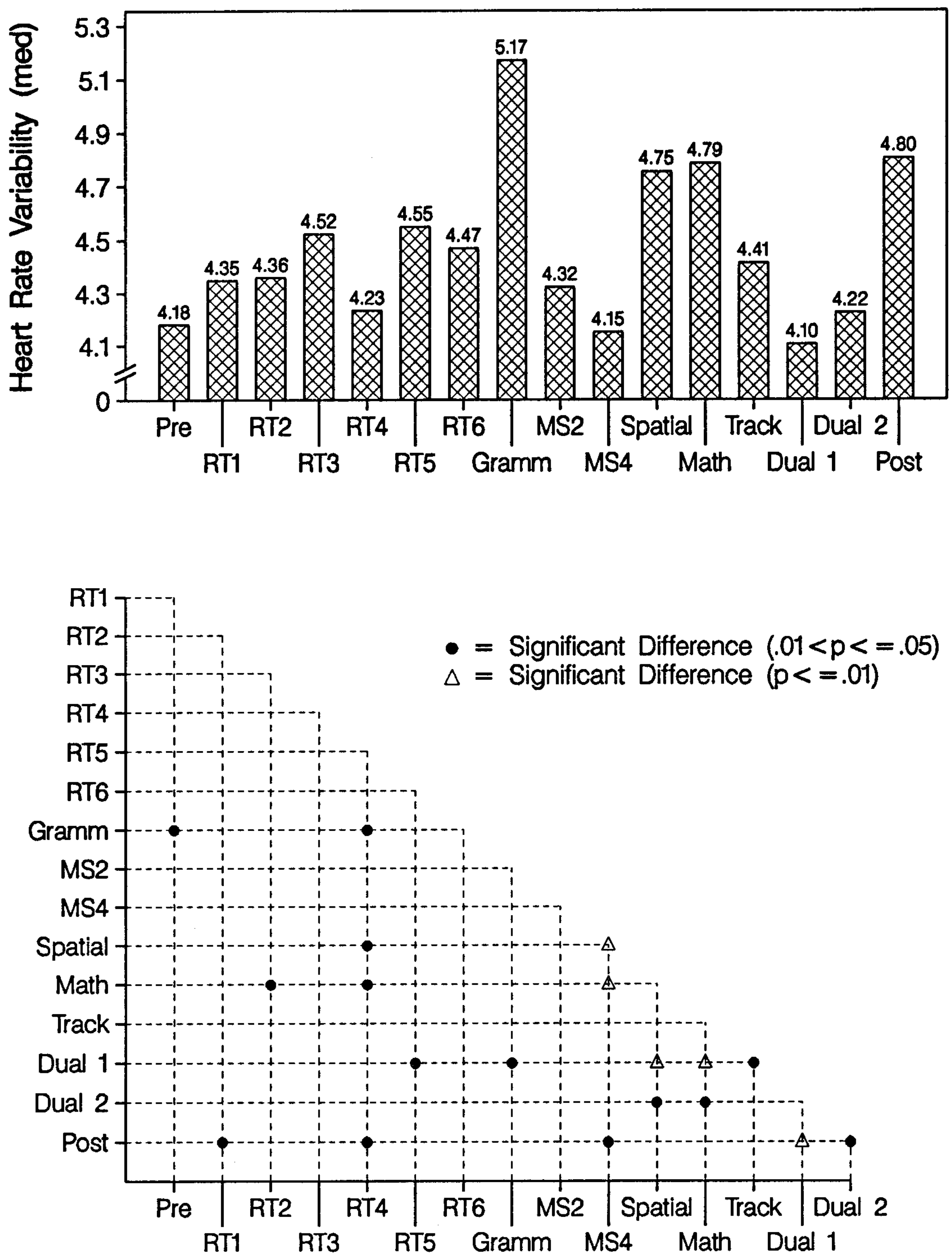


Figure 31. Top: Mean heart rate variability (medium 0.06–0.14 Hz) for baselines and STRES battery tasks for Session 2.
Bottom: Matrix of significance of between task comparisons.

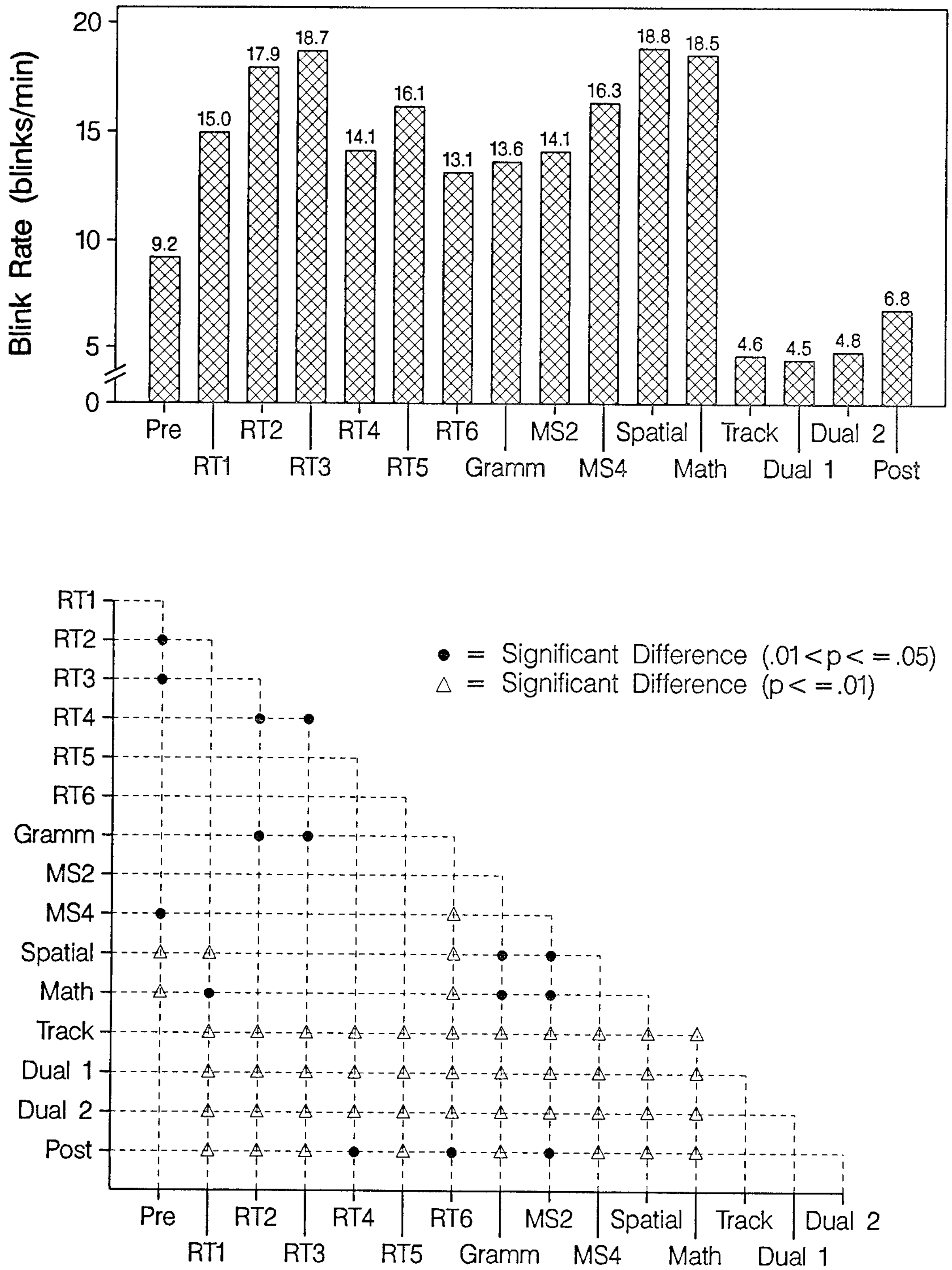
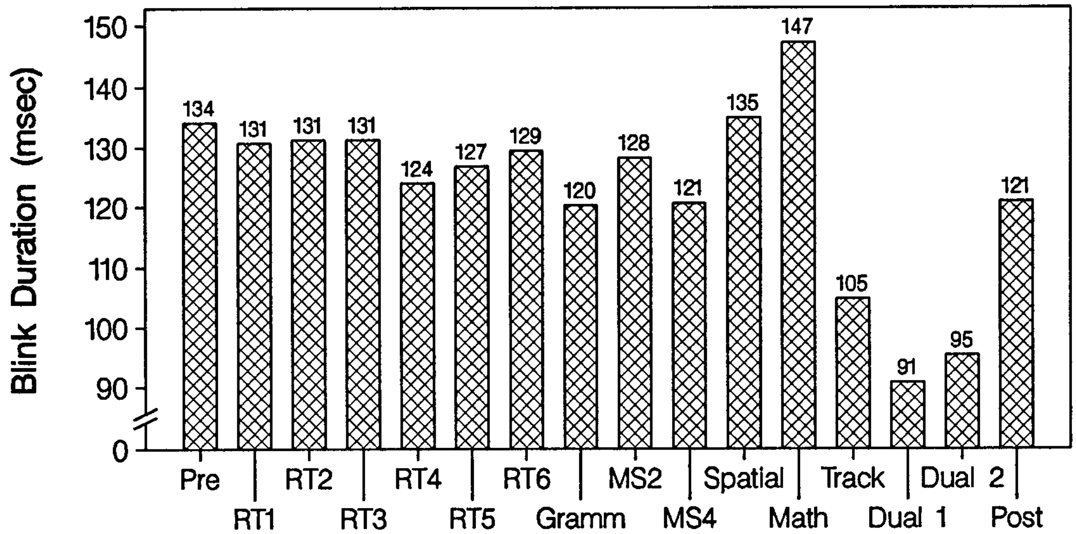


Figure 32. Top: Mean blink rate for baselines and STRES battery tasks for Session 2. Bottom: Matrix of significance of between task comparisons.



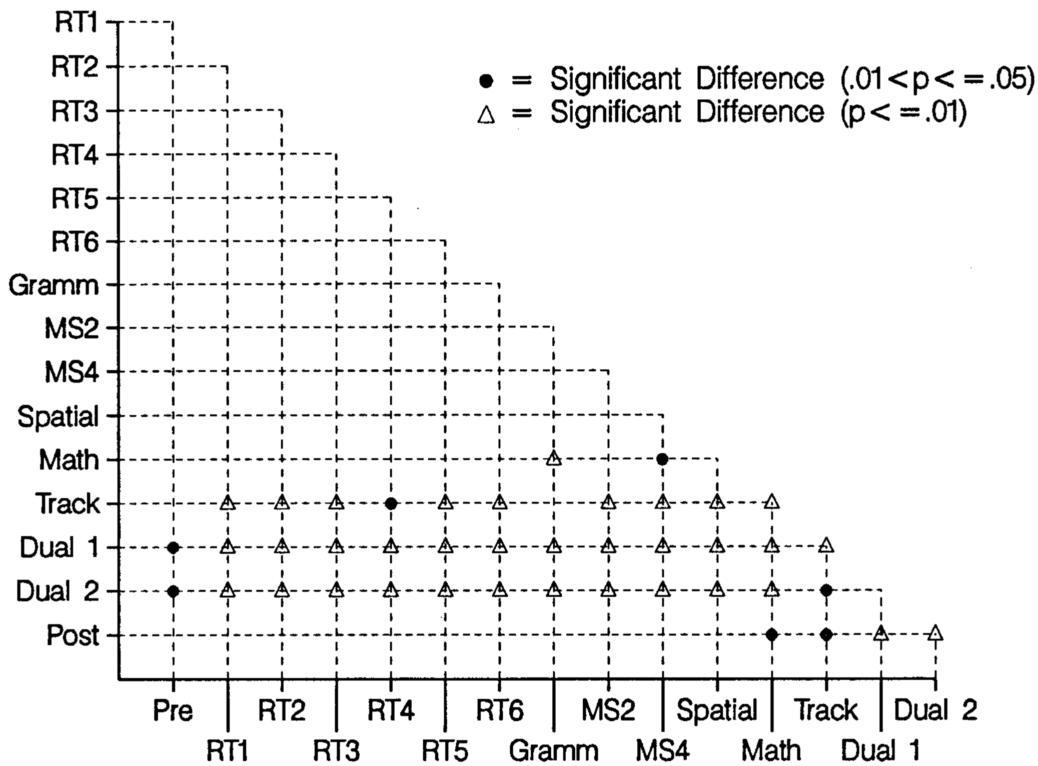


Figure 33. Top: Mean blink duration for baselines and STRES battery tasks for Session 2.
Bottom: Matrix of significance of between task comparisons.

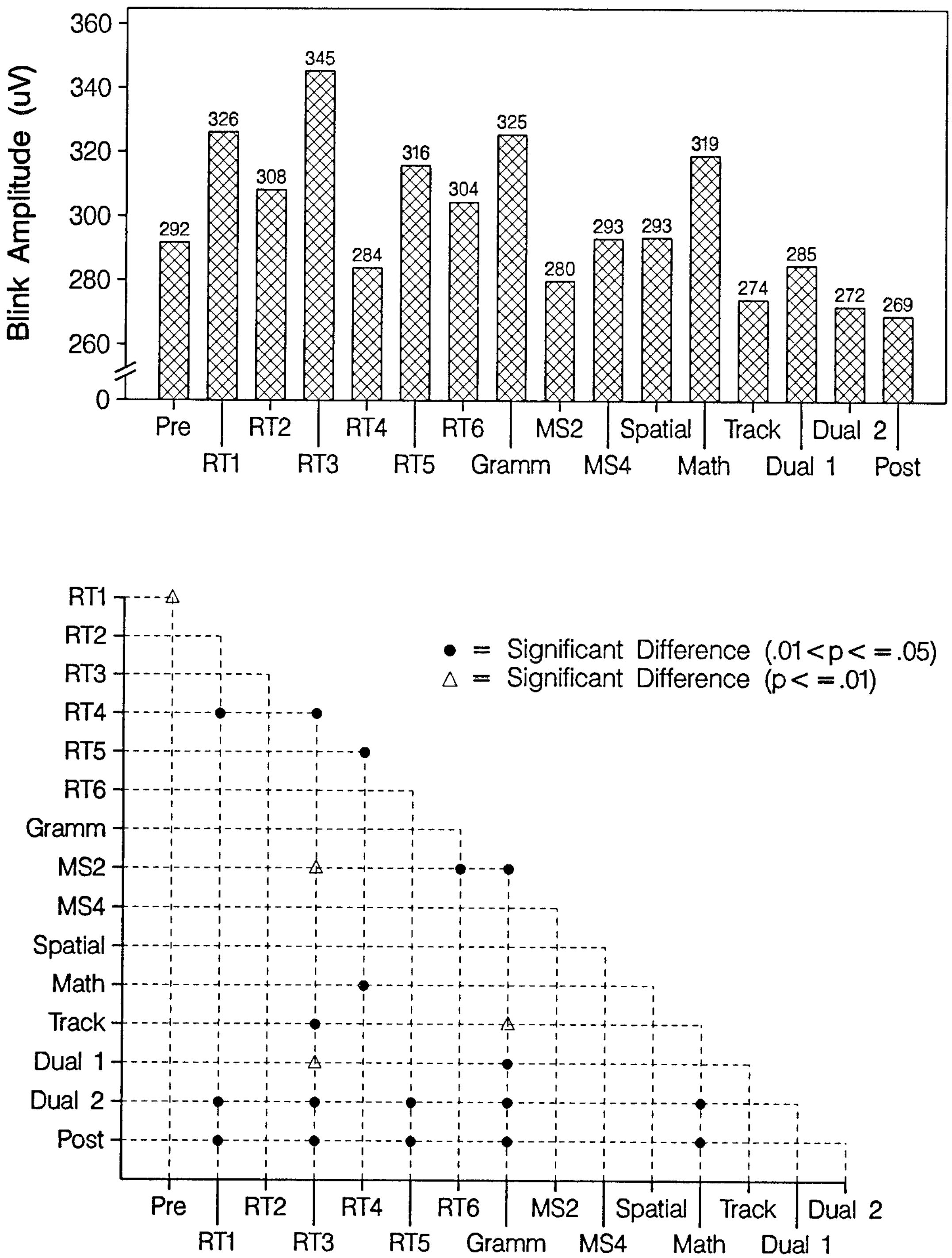
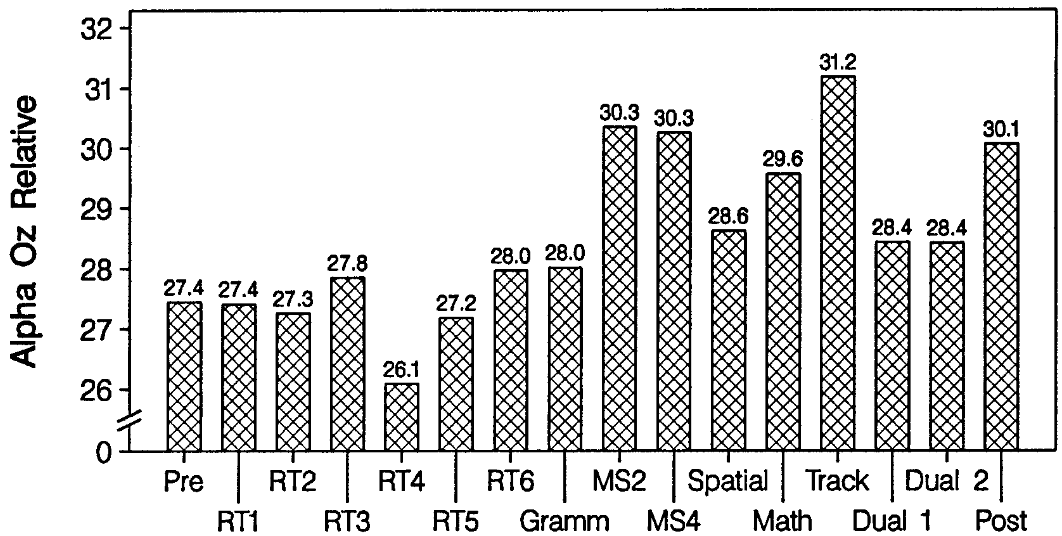


Figure 34. Top: Mean blink amplitude for baselines and STRES battery tasks for Session 2.
Bottom: Matrix of significance of between task comparisons.



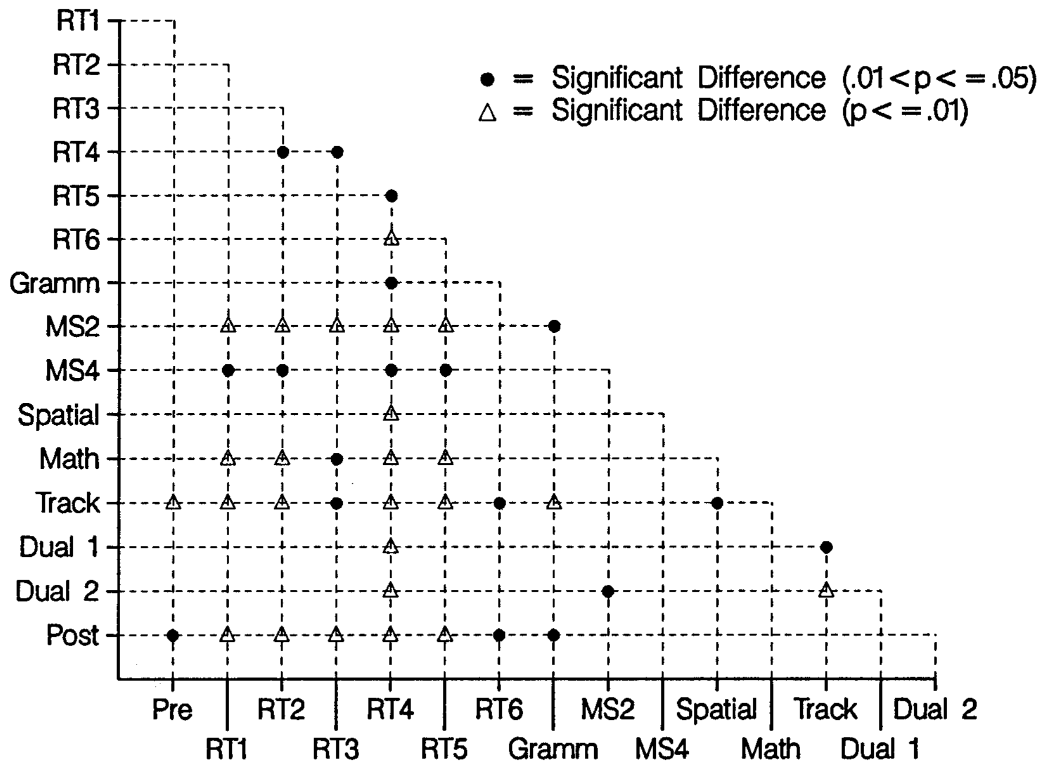


Figure 35. Top: Mean relative power at Oz in the alpha EEG band for baselines and STRES battery tasks for Session 2.
Bottom: Matrix of significance of between task comparisons.

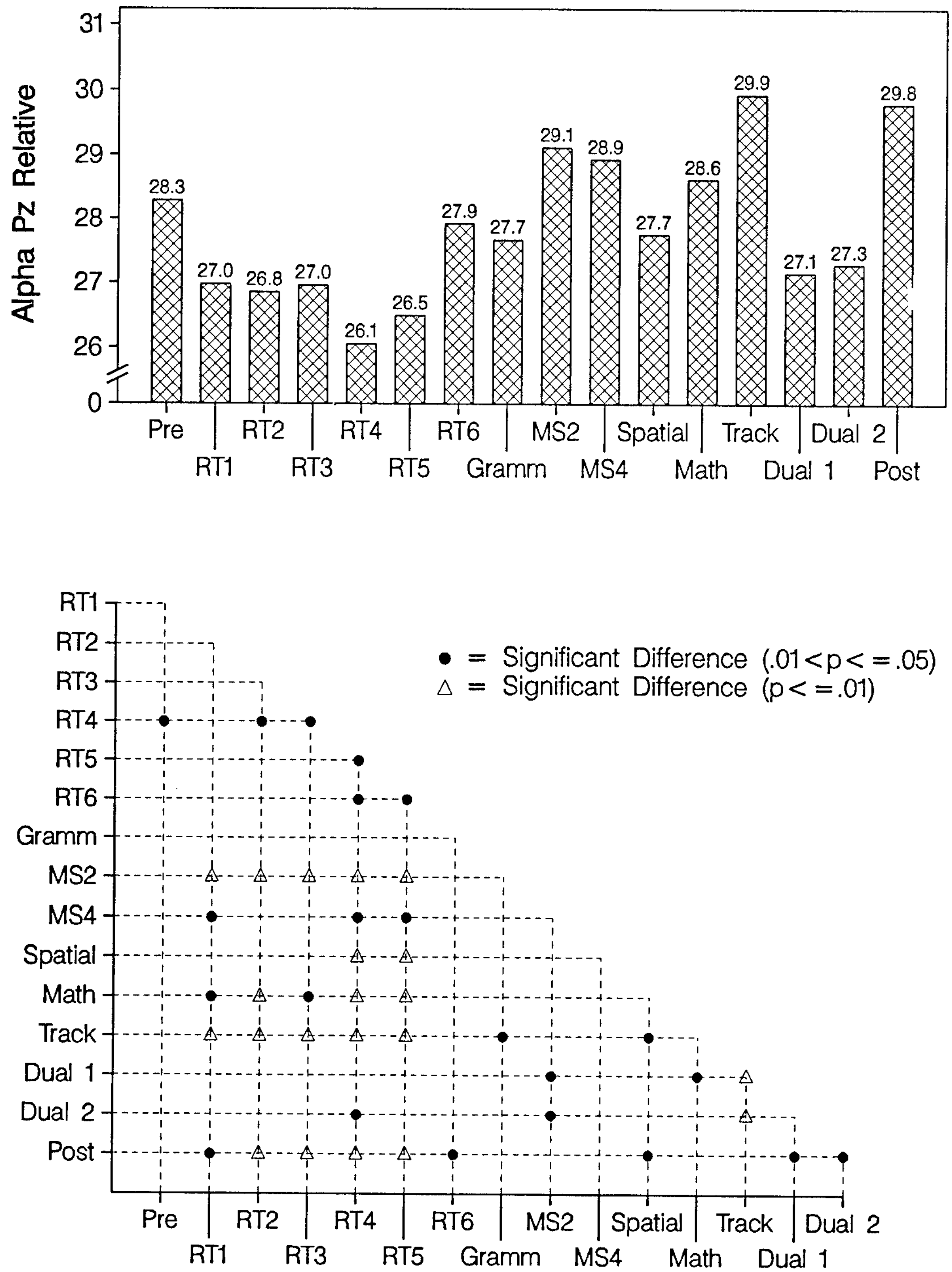
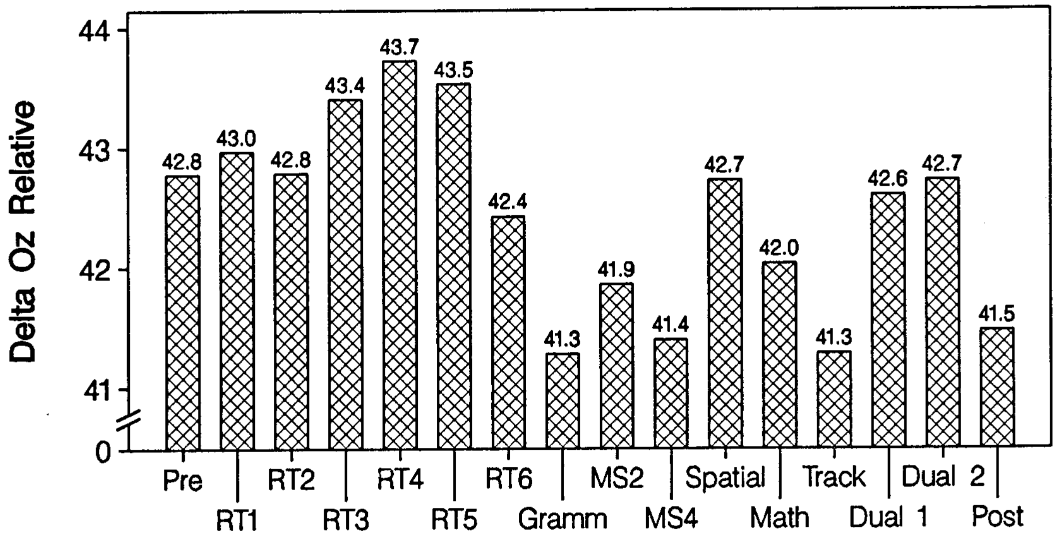


Figure 36. Top: Mean relative power at Pz in the alpha EEG band for baselines and STRES battery tasks for Session 2.
Bottom: Matrix of significance of between task comparisons.



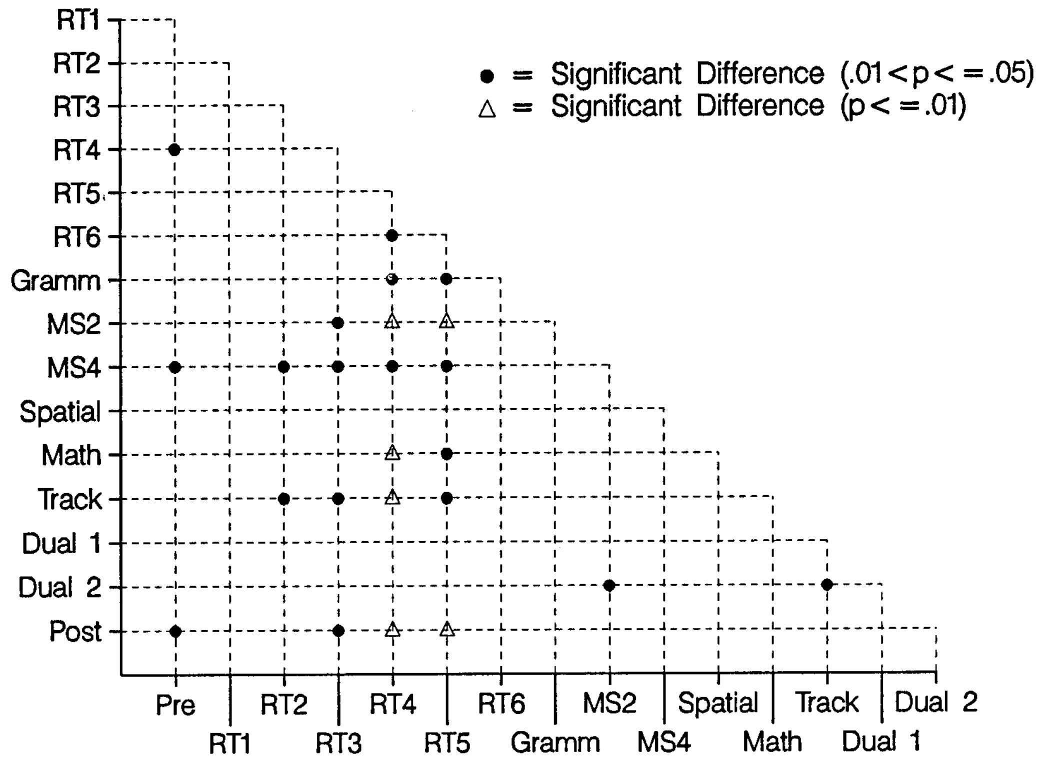


Figure 37. Top: Mean relative power at Oz in the delta EEG band for baselines and STRES battery tasks for Session 2.
Bottom: Matrix of significance of between task comparisons.

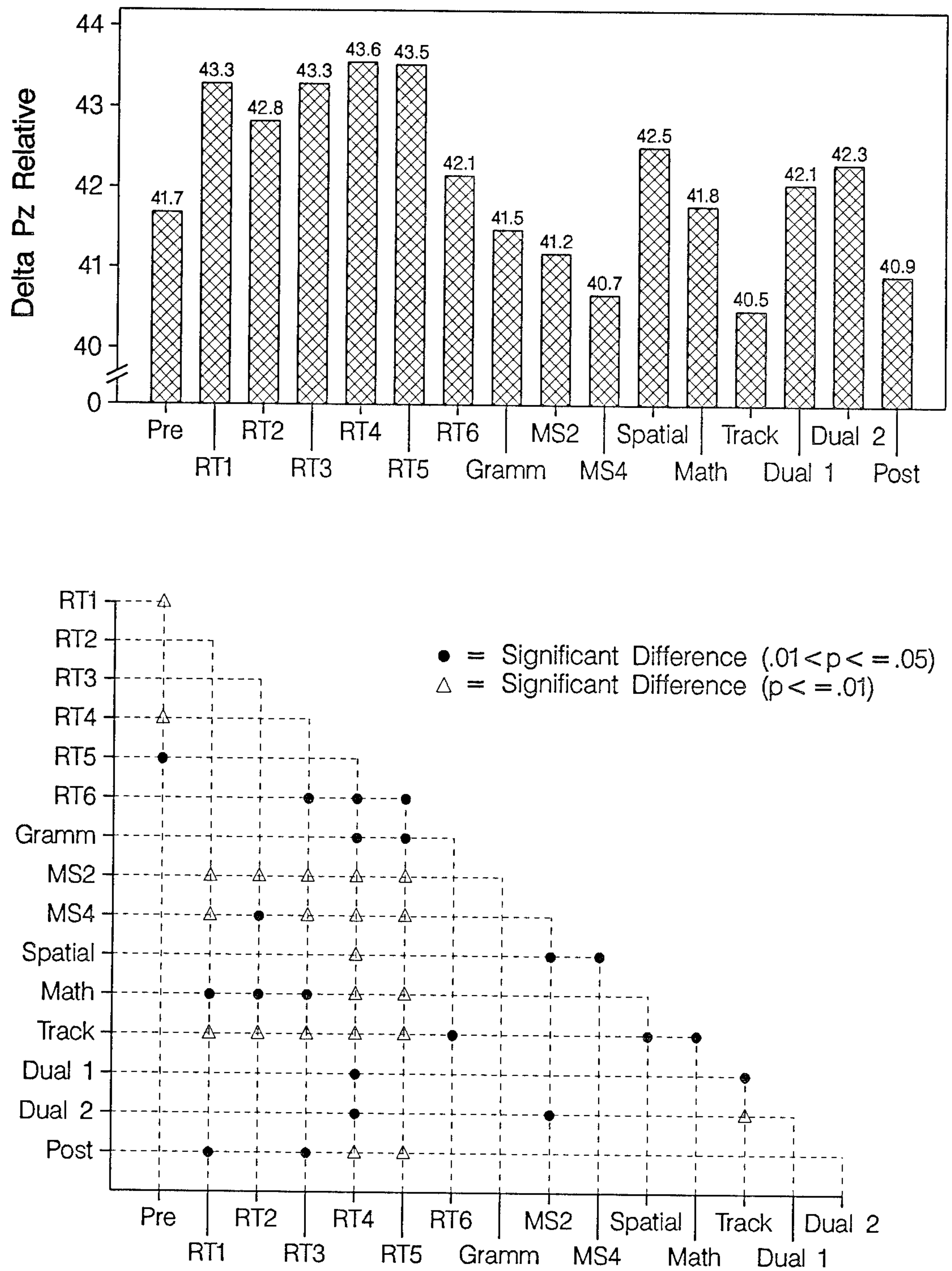
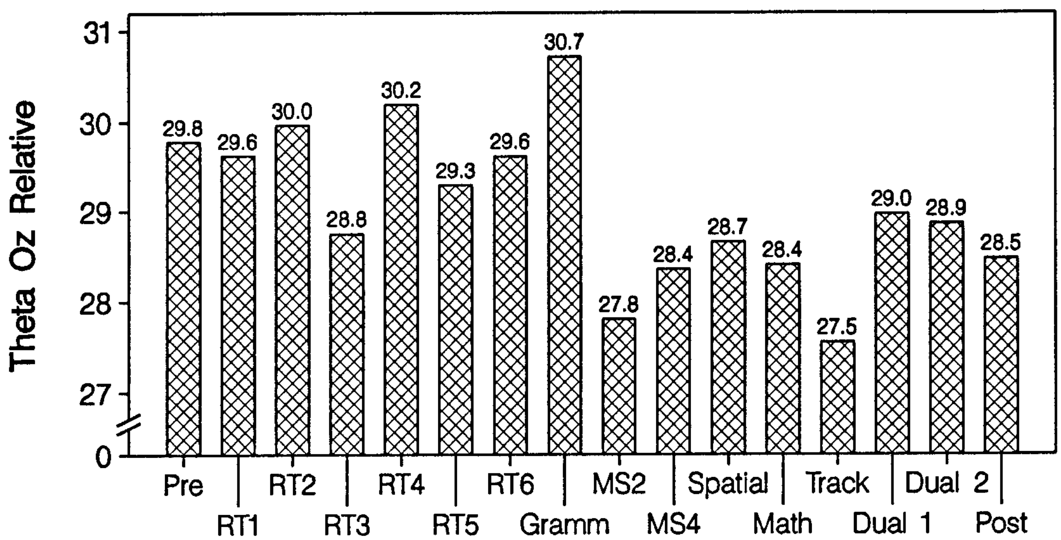


Figure 38. Top: Mean relative power at Pz in the delta EEG band for baselines and STRES battery tasks for Session 2.
Bottom: Matrix of significance of between task comparisons.



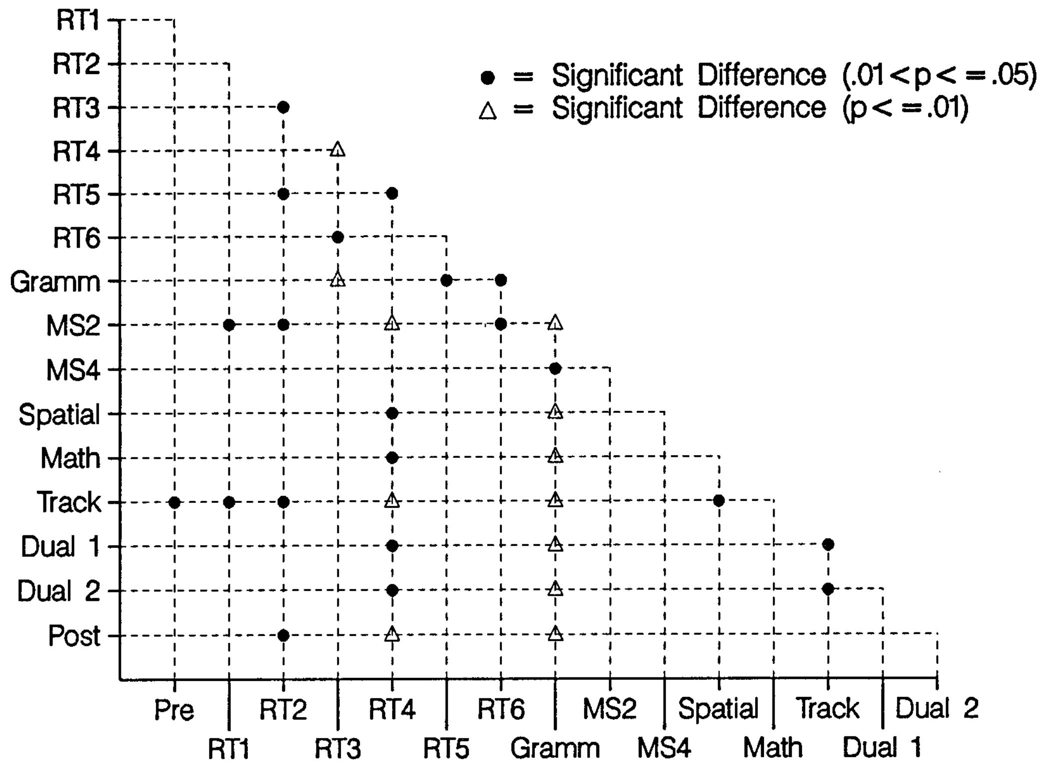


Figure 39. Top: Mean relative power at Oz in the theta EEG band for baselines and STRES battery tasks for Session 2.
Bottom: Matrix of significance of between task comparisons.

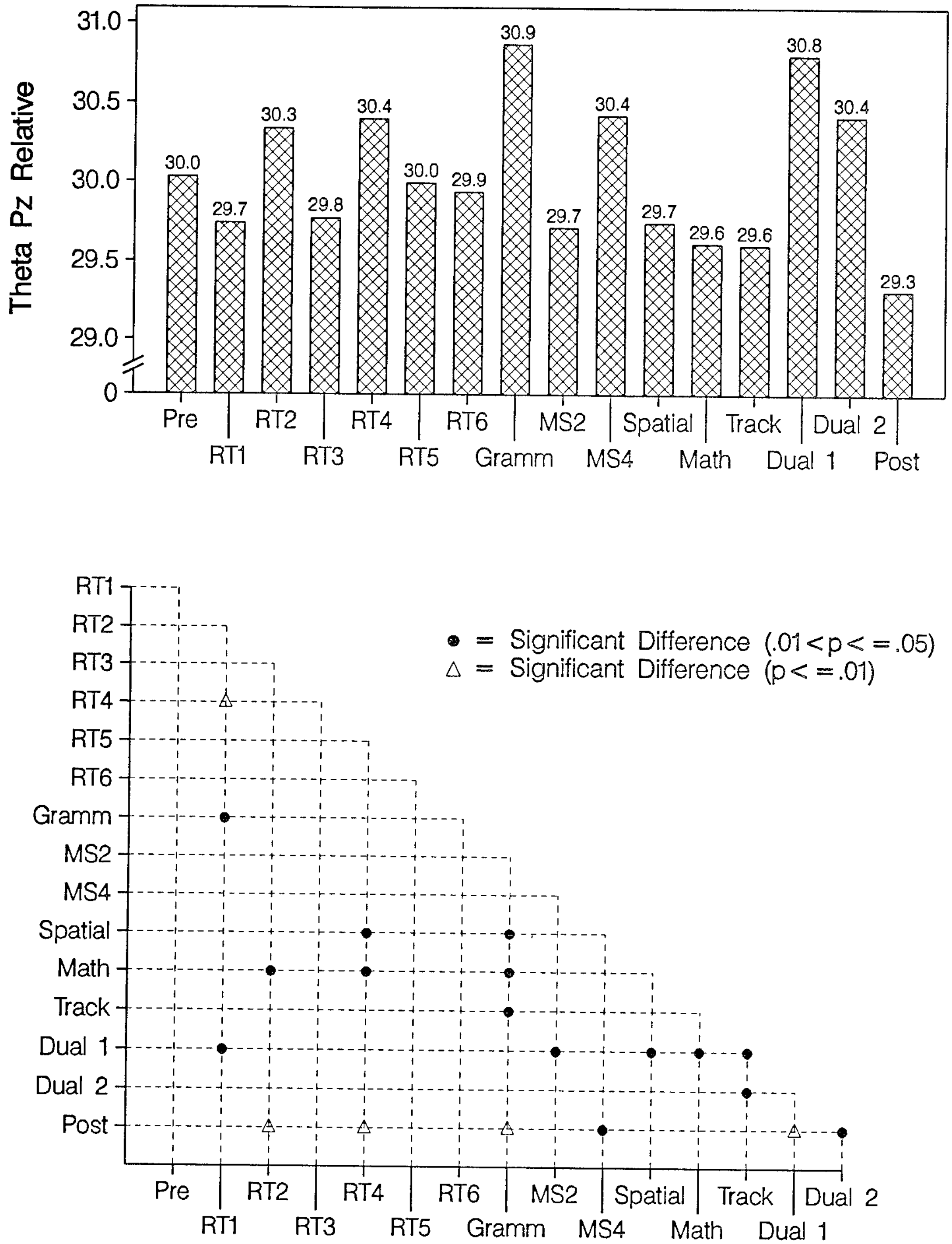


Figure 40. Top: Mean relative power at Pz in the theta EEG band for baselines and STRES battery tasks for Session 2.
Bottom: Matrix of significance of between task comparisons.

increased blink duration as well. This difference is obvious in the plots of Figure 32, which shows the rate of blinking for all the tasks on the top, and the number of significant between-task comparisons on the bottom.

Significantly reduced blink durations during the tracking tasks is seen in Figure 33, which portrays eye blink duration for all the tasks, and displays a matrix of significant between-task differences. The math task appears to have produced blinks of greater duration than those produced by other tasks.

The trend is not so clear for eye blink amplitude, shown in Figure 34; Dual Tasks 2 and the post-baseline generated low values of amplitude, white RT 3 and the grammatical reasoning task were associated with higher amplitude values.

Figures 35-40 show relative power at alpha, delta, and theta EEG bands at Pz and Oz for all tasks, and the matrix indicates which tasks differed significantly from one another. The relatively lower power values for alpha at RT 4 and RT 5 engendered many significant differences; reaction time tasks in general showed many differences from other tasks for this band. Greater power values for delta and theta for RT 4 and RT 5 resulted in differences with other tasks, and again, there were several significant findings for the reaction time tasks. Although grammatical reasoning produced a fairly low power value for theta, its delta magnitude resulted in several significant differences with other tasks, especially at Oz. More specifically, relative power at Oz and Pz for alpha was generally low for reaction time tasks, especially RT 4 and RT 5, compared to the other STRES Battery tasks. Math, tracking, the memory search tasks, and the post-baseline all had relatively greater alpha power than the reaction time tasks. When performed singly, tracking and the memory search tasks had greater relative alpha than when they were combined (Dual 1 and Dual 2 tasks).
Relative delta was greater for reaction time tasks compared to the other STRES Battery tasks. Again, the memory search tasks, tracking, and math all showed lower relative power compared to most RT tasks. Memory search and tracking produced

greater relative power when combined, compared to when they were performed alone. Relative theta was greater in general for RT tasks (especially for RT 4) than for the other STRES Battery tasks, except grammatical reasoning, which was significantly greater than for almost every other task. Relative theta increased when tracking and the memory search tasks were combined compared to when they were performed under single-task conditions.

Absolute power values for Session 2 are seen in Figures 41-48. Relatively low total power at Oz for RT 1, RT 2, and RT 3 shows up as different from power at Dual Tasks 2 ($t=-2.245$, $p=.0486$; $t=-2.248$, $p=.0483$; $t=-2.229$, $p=.0443$, respectively) and post-baseline ($t=2.306$, $p=.0438$; $t=2.286$, $p=.0453$; $t=2.700$; $p=.0223$, respectively), while total power at Pz shows no such trend. Absolute alpha appears higher for the central processing tasks than the reaction time tasks and the relatively low value at RT 4 differs from many other tasks. Delta Oz and delta Pz look greatly different from one another; most of the significant differences at Pz are due to the small delta value at post-baseline, while the large number of significant differences for Oz are attributable to the large delta values for the reaction time tasks.

Similarly, theta at Oz shows several reaction time task differences due to high theta, while theta at Pz shows MS 4 as having significantly greater theta than three other tasks.

Since different stimuli were used among the various STRES Battery tasks, it is not appropriate to directly compare evoked potentials across tasks. Groups of tasks however, did present similar stimulus displays. The reaction time tasks, for instance, always presented the same number of stimulus elements, even in the degraded stimulus condition. The N1 amplitudes tended to be smaller for RT 4 and RT 5 than for the other reaction time tasks. P2 amplitudes were significantly greater at Pz and Oz for Dual Task 1 and Dual Task 2 compared to the analogous MS 2 task. P2 latency was significantly shorter for Dual Task 1 and Dual Task 2 compared to MS 2 at Pz. The

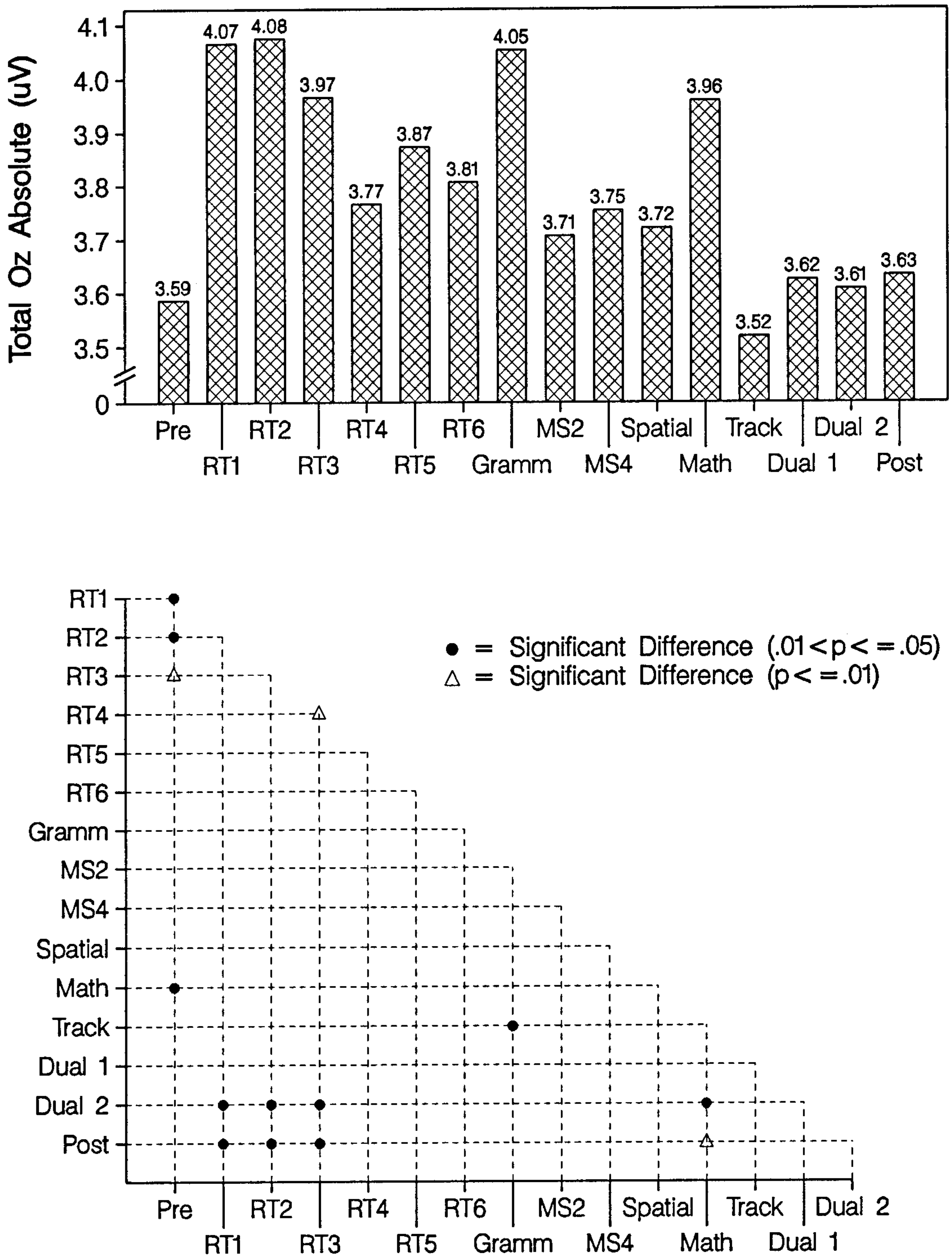
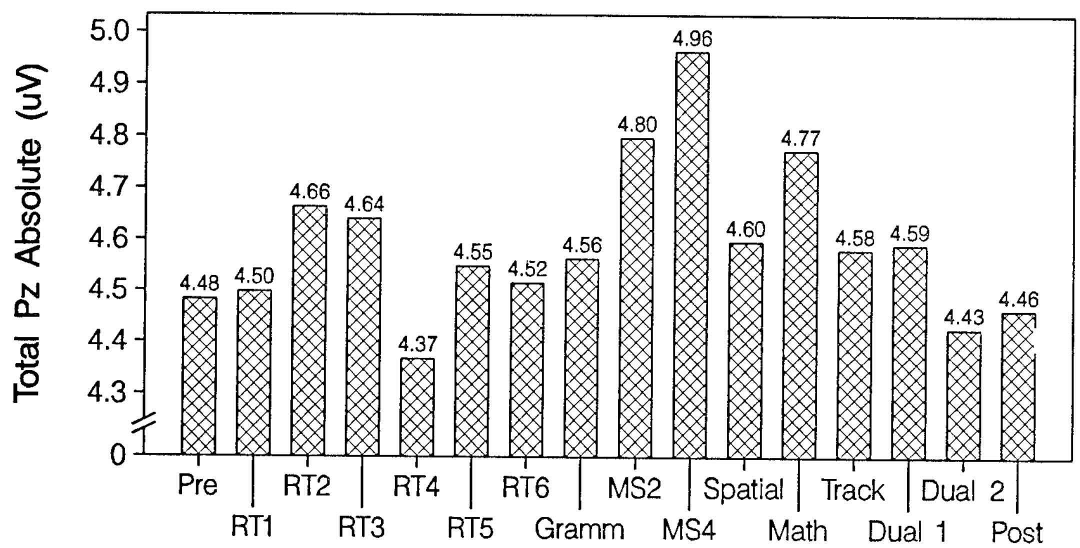


Figure 41. Top: Total EEG power at Oz for baselines and STRES battery tasks for Session 2.
Bottom: Matrix of significance of between task comparisons.



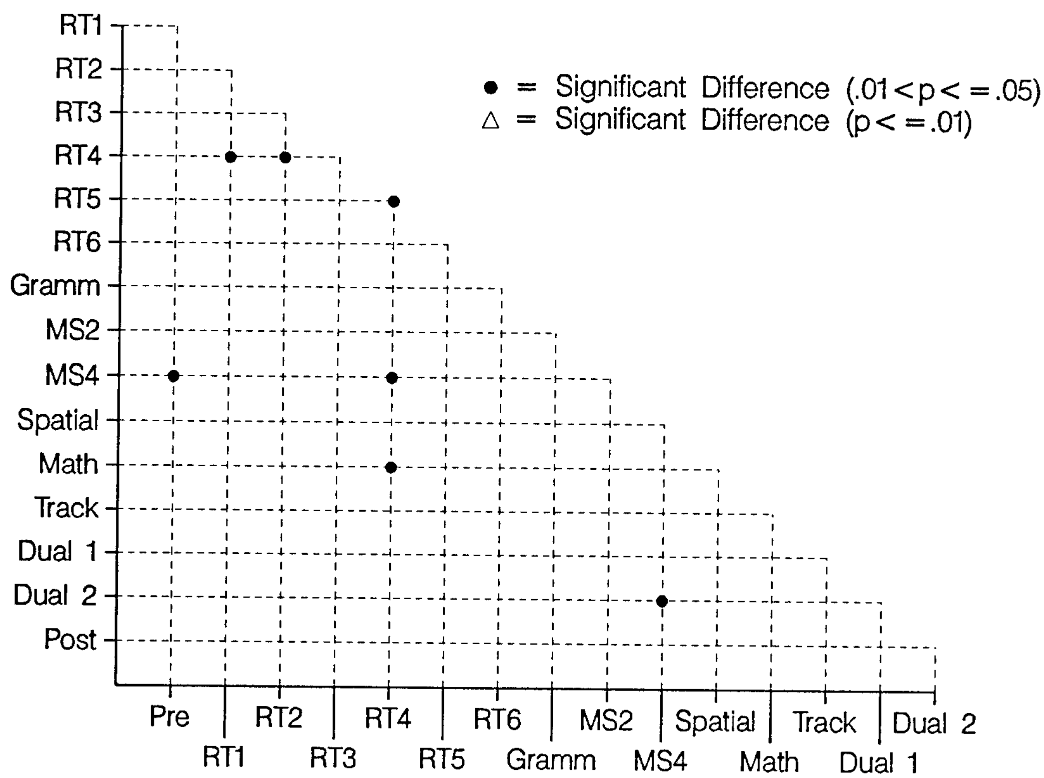
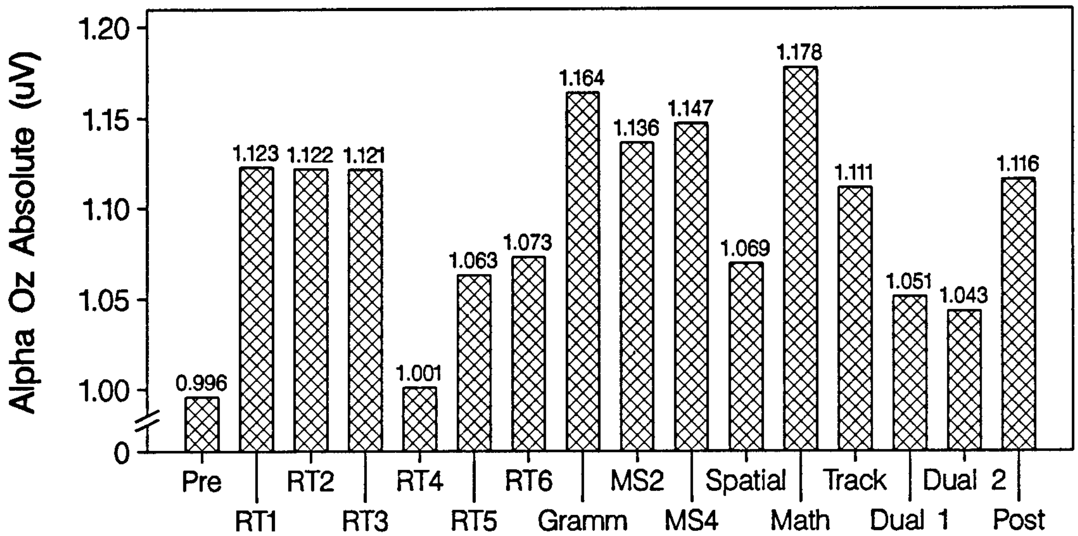


Figure 42. Top: Total EEG power at Pz for baselines and STRES battery tasks for Session 2.
Bottom: Matrix of significance of between task comparisons.



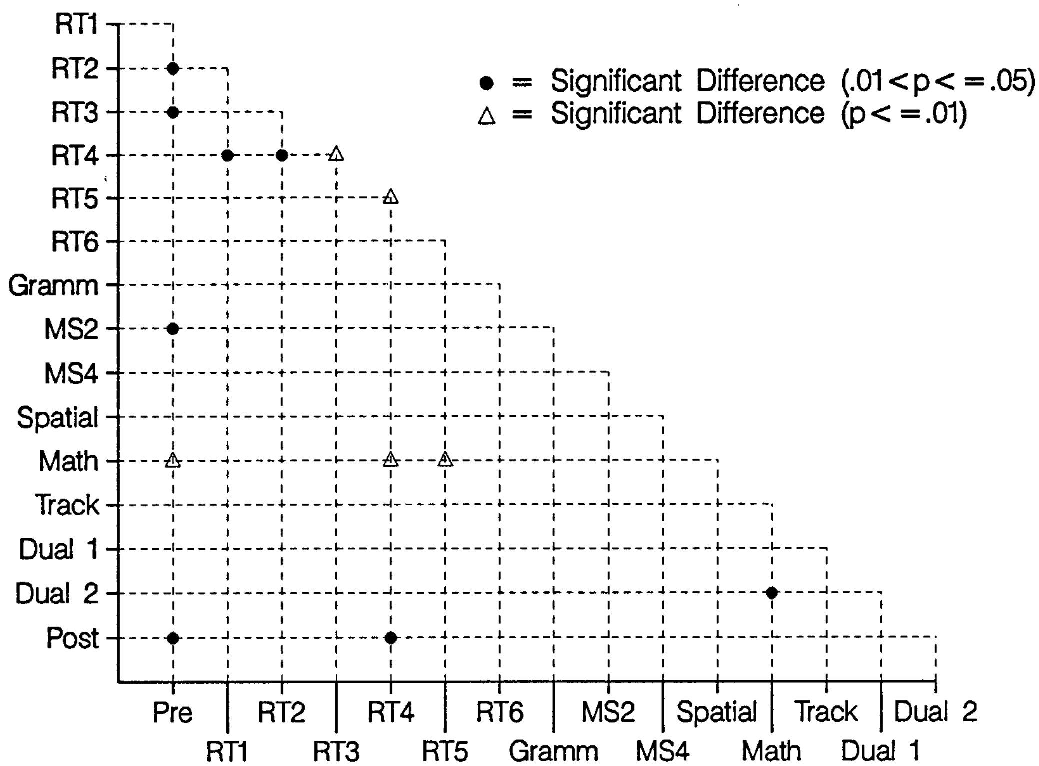
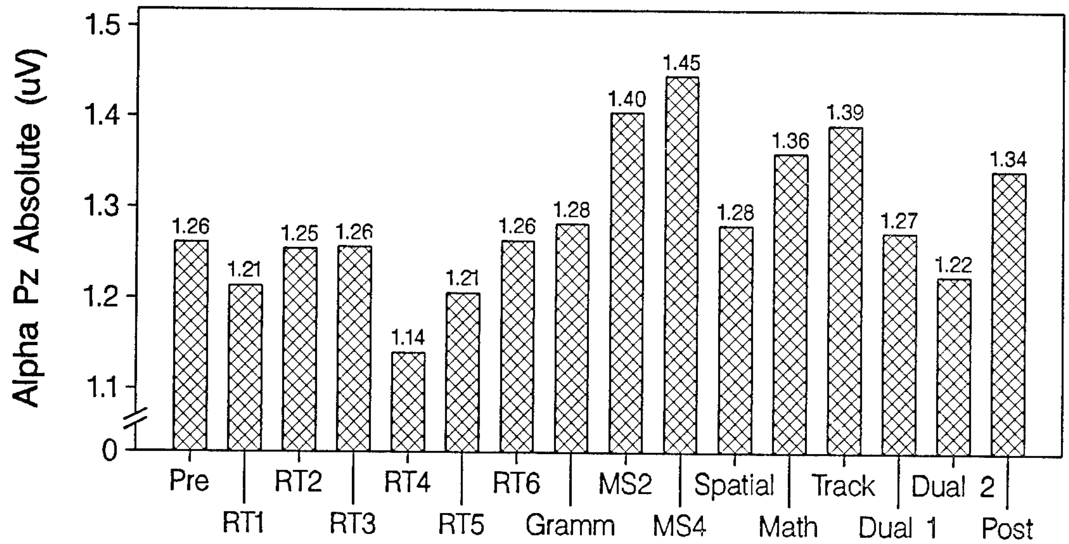


Figure 43. Top: Absolute power at Oz in the alpha EEG band for baselines and STRES battery tasks for Session 2.
Bottom: Matrix of significance of between task comparisons.



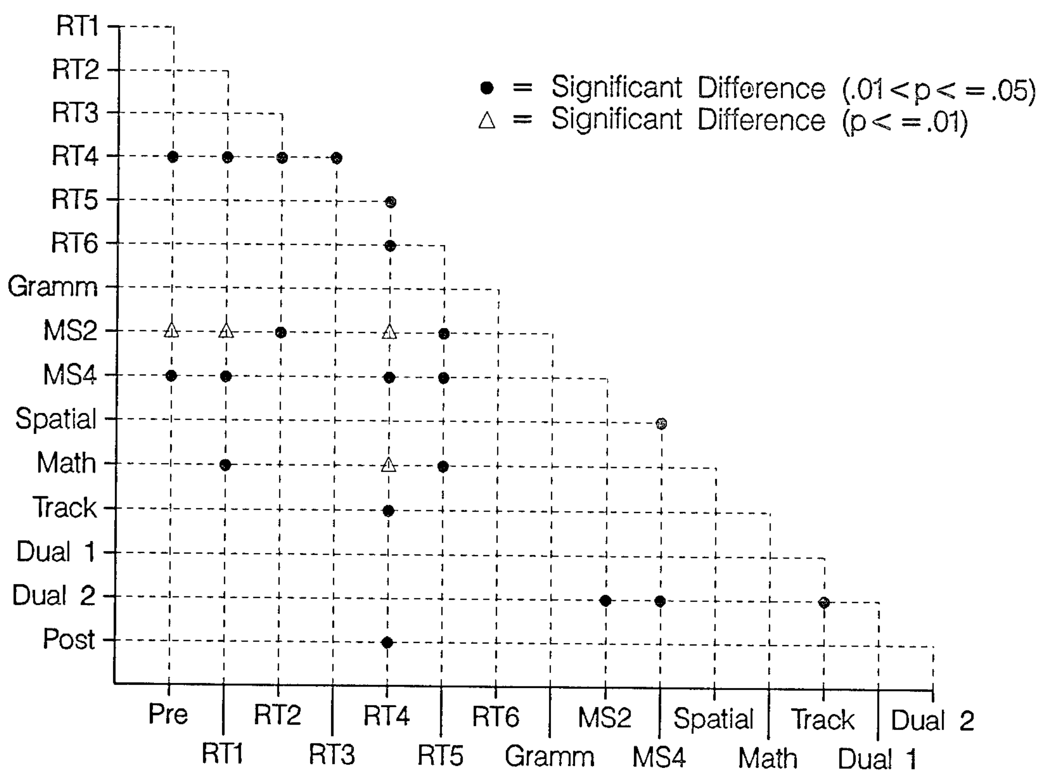


Figure 44. Top: Absolute power at Pz in the alpha EEG band for baselines and STRES battery tasks for Session 2.
Bottom: Matrix of significance of between task comparisons.

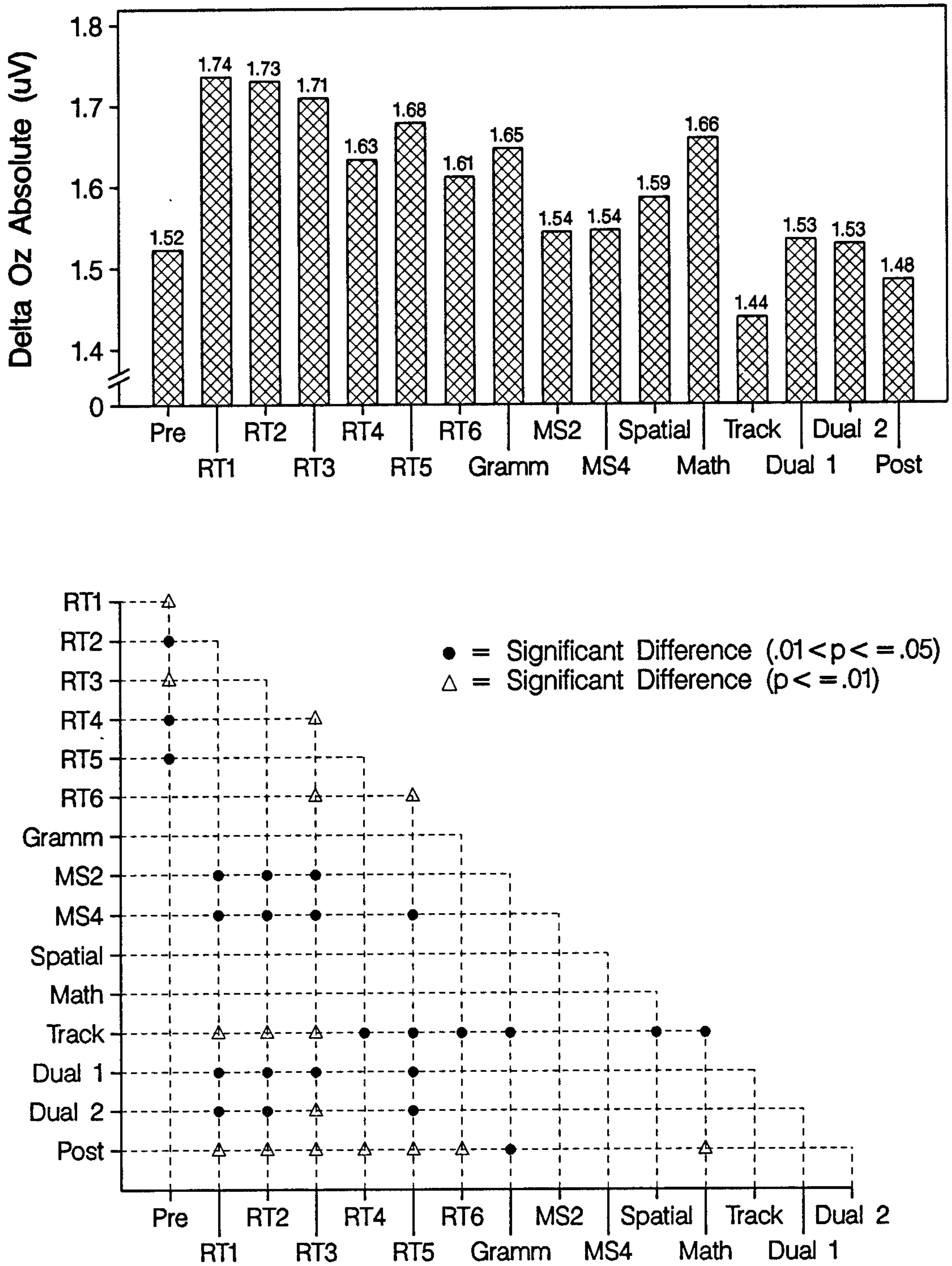
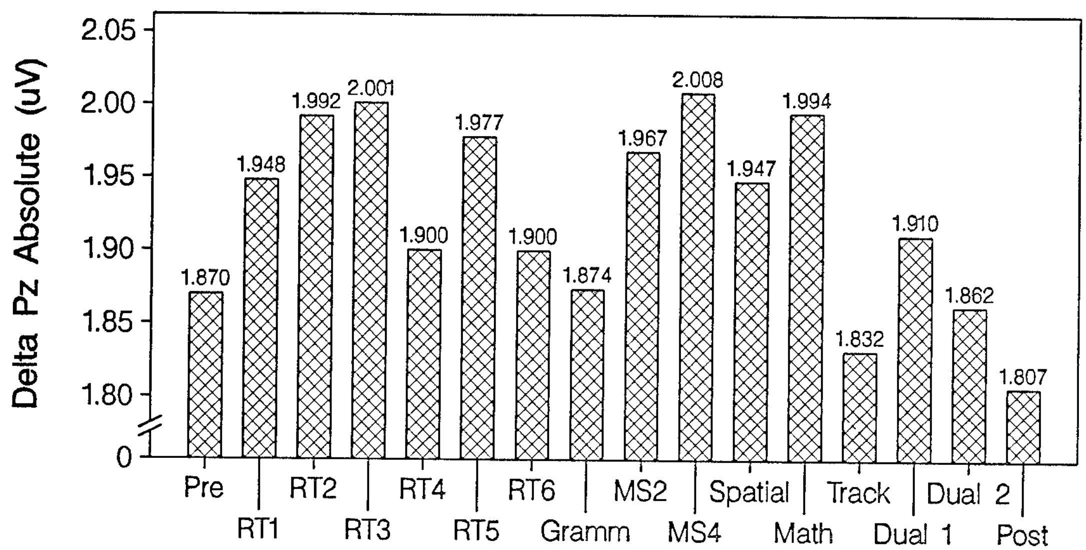


Figure 45. Top: Absolute power at Oz in the delta EEG band for baselines and STRES battery tasks for Session 2.
Bottom: Matrix of significance of between task comparisons.



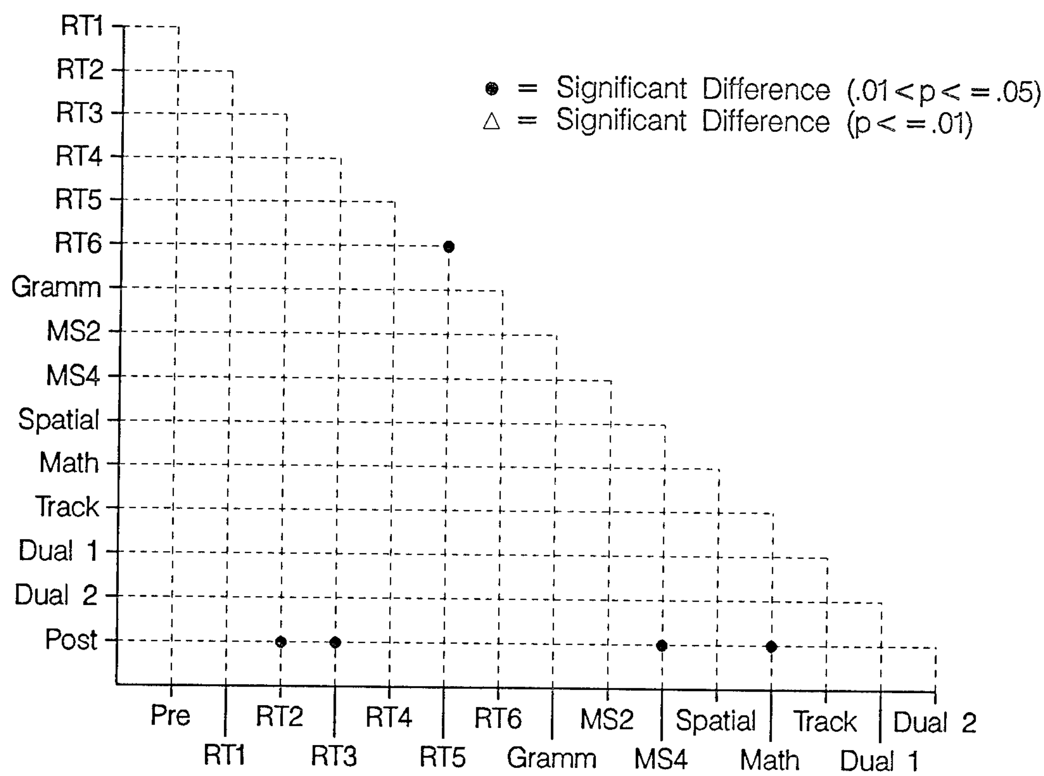
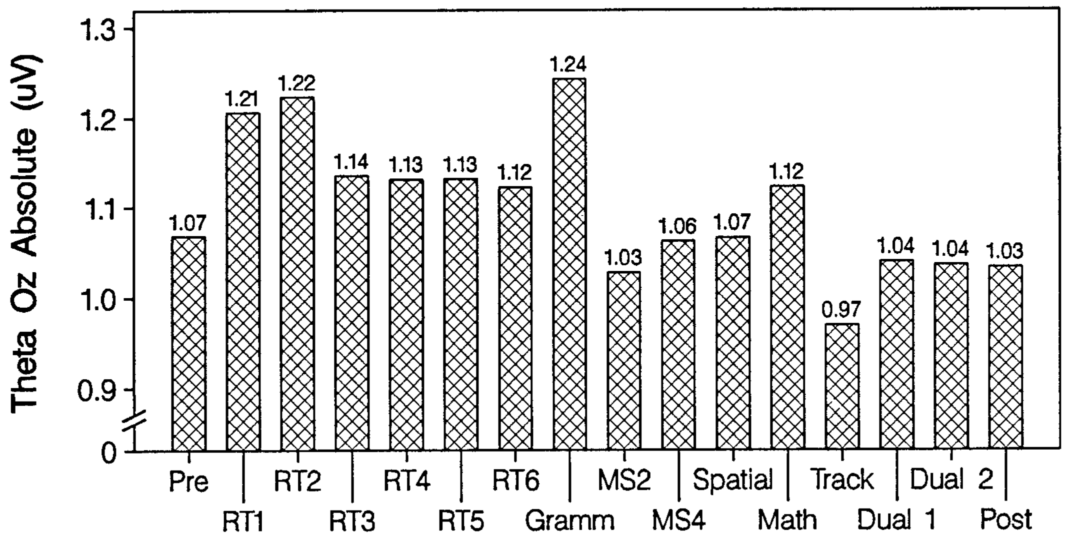


Figure 46. Top: Absolute power at Pz in the delta EEG band for baselines and STRES battery tasks for Session 2.
Bottom: Matrix of significance of between task comparisons.



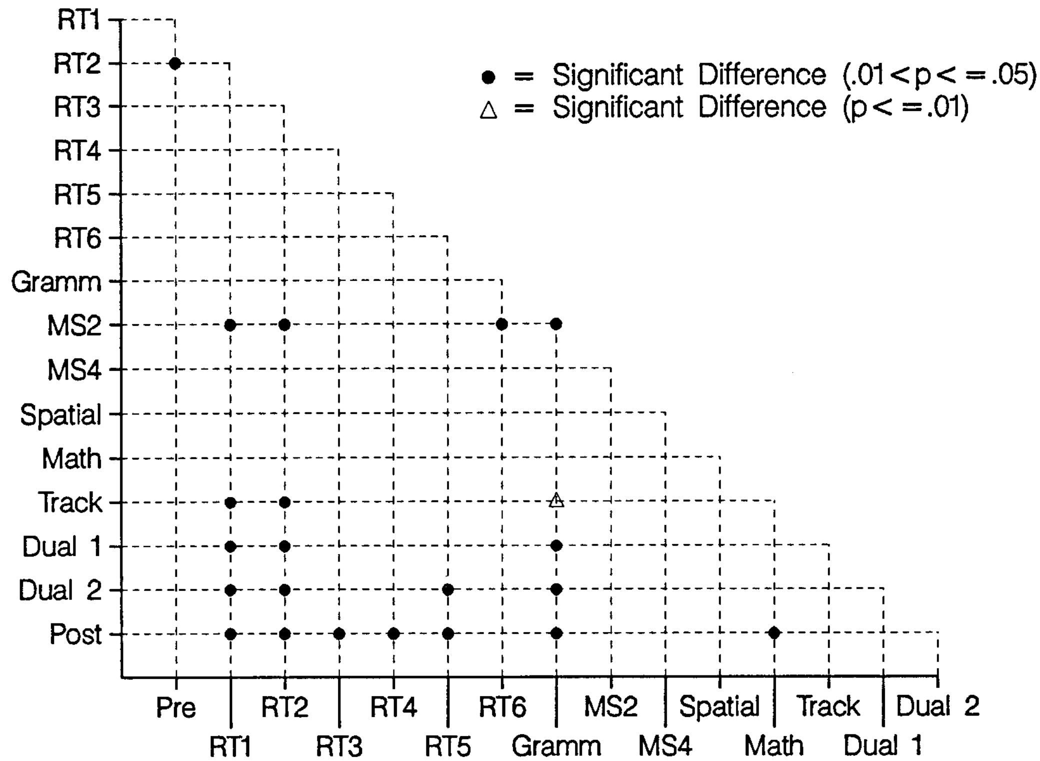
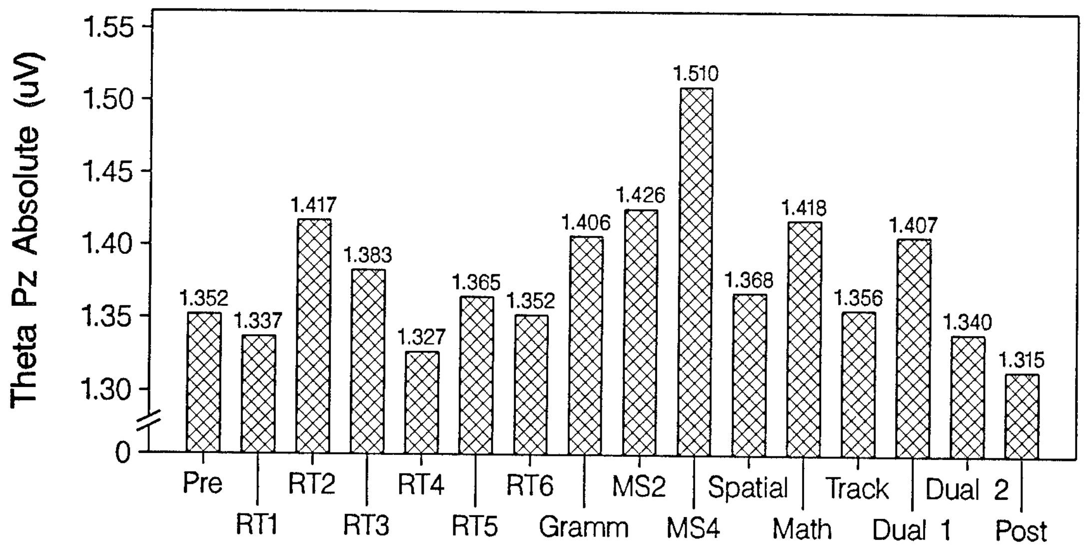


Figure 47. Top: Absolute power at Oz in the theta EEG band for baselines and STRES battery tasks for Session 2.
Bottom: Matrix of significance of between task comparisons.



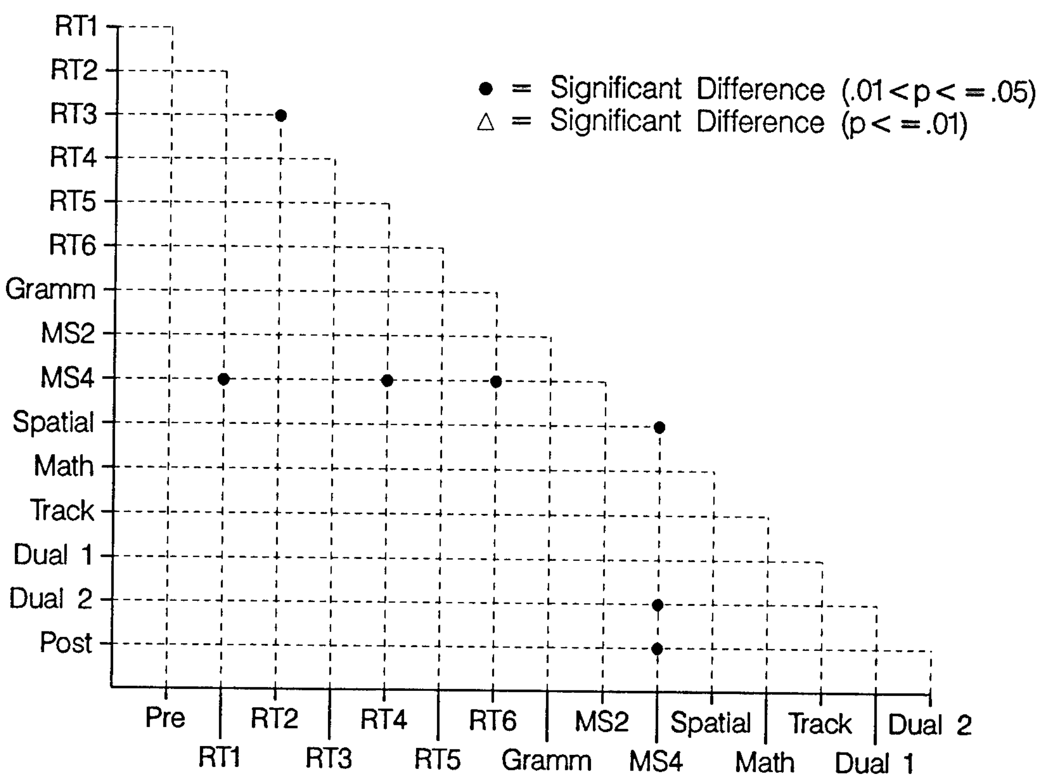
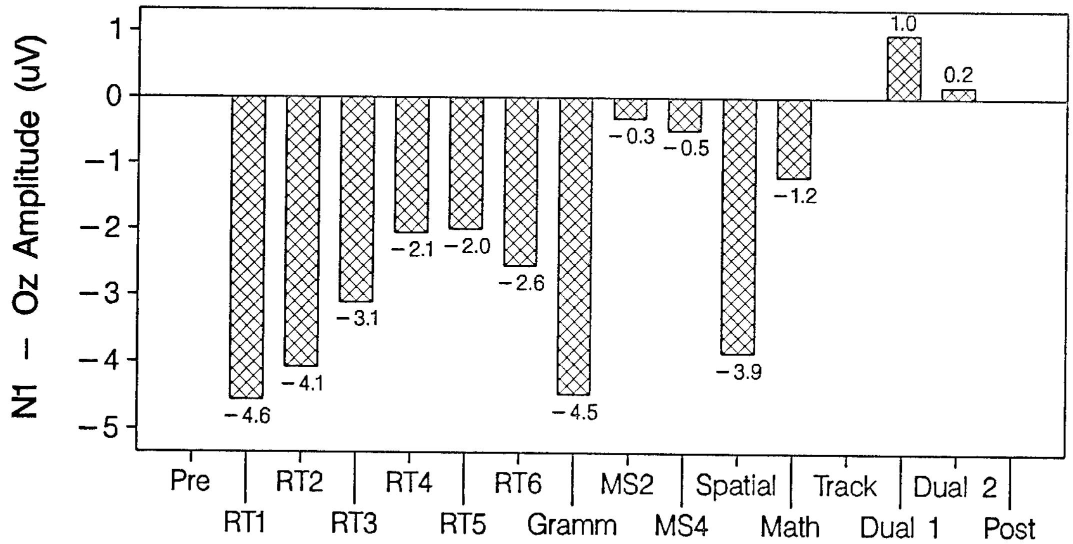


Figure 48. Top: Absolute power at Pz in the theta EEG band for baselines and STRES battery tasks for Session 2.
Bottom: Matrix of significance of between task comparisons.

relatively short RT 3 latency at P2 differed significantly from RT 1, RT 4, and RT 5 at Oz, and from RT 4 at Pz. The dual tasks presented identical stimuli, as did their component tasks, MS 2 and MS 4. Evoked potential amplitudes over tasks for Session 2 are seen in Figures 49-54. Latencies are plotted in Figures 55-60.
The N1 amplitudes tended to be smaller for RT 4 and RT 5 than for the other reaction time tasks. P2 amplitudes were significantly greater at Pz and Oz for Dual Task 1 and Dual Task 2 compared to the analogous MS 2 task. P2 latency was significantly shorter for Dual Task 1 and Dual Task 2 compared to MS 2 at Pz. The relatively short RT 3 latency at P2 differed significantly from RT 1, RT 4, and RT 5 at Oz, and from RT 4 at Pz.

Figure 61 indicates subjects' subjective reports about task difficulty. The scores on each subscale and the weighting factor were multiplied to produce these composite scores. Subjects indicated that the greatest demands were put on them during both Dual-Tasks, RT 5, and grammatical reasoning tests of the STRES Battery. Relatively low demands were required by the tracking, spatial, memory search and the remaining reaction time tasks.

Ordering these tasks by their subjective difficulty produces some patterns with the physiological measures that are worth noting. Relative theta at Pz, shows high power for the dual-task and grammatical reasoning tests, which were perceived as being difficult tasks, and the lowest power for the tracking task, which was apparently perceived as the easiest task of the STRES Battery. Relative alpha produced the predictable reverse relationship, with high power values for tracking (an easy task) and low values for the dual tasks and the grammatical reasoning task.



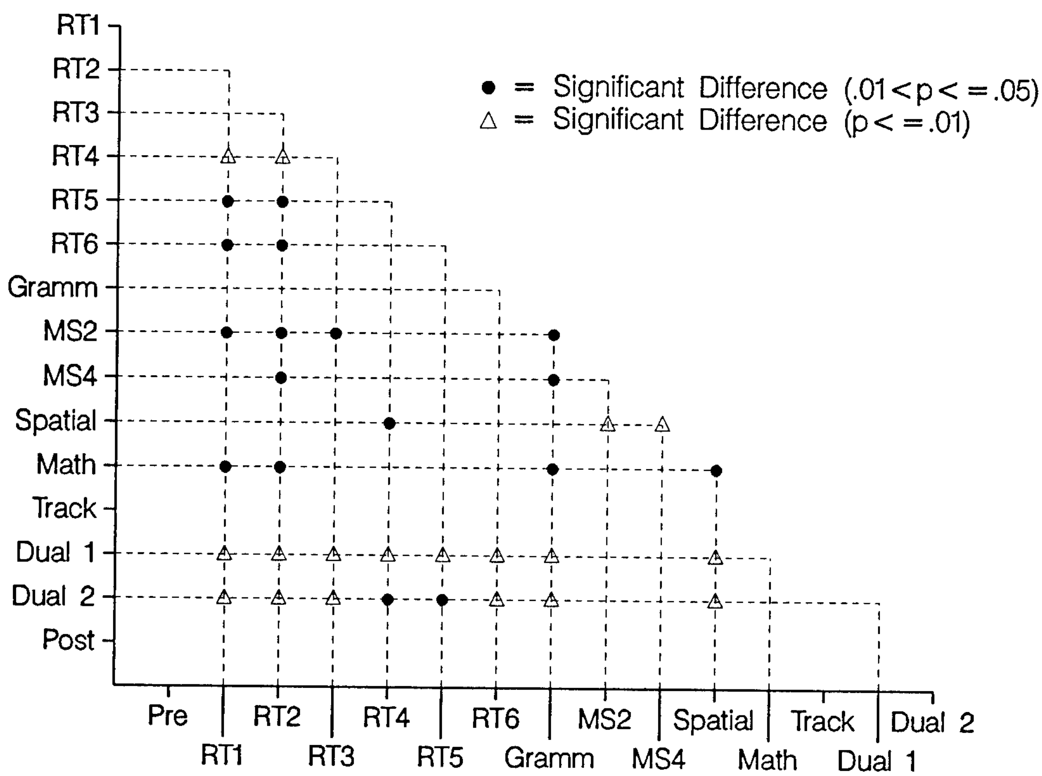
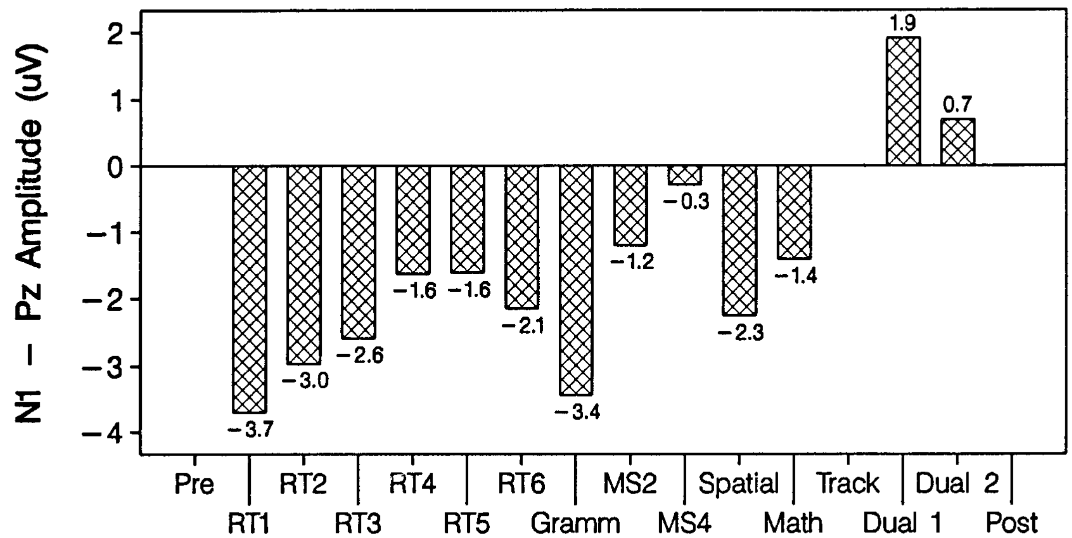


Figure 49. Top: Mean amplitude at Oz for N1 for STRES battery tasks for Session 2. Bottom: Matrix of significance of between task comparisons.



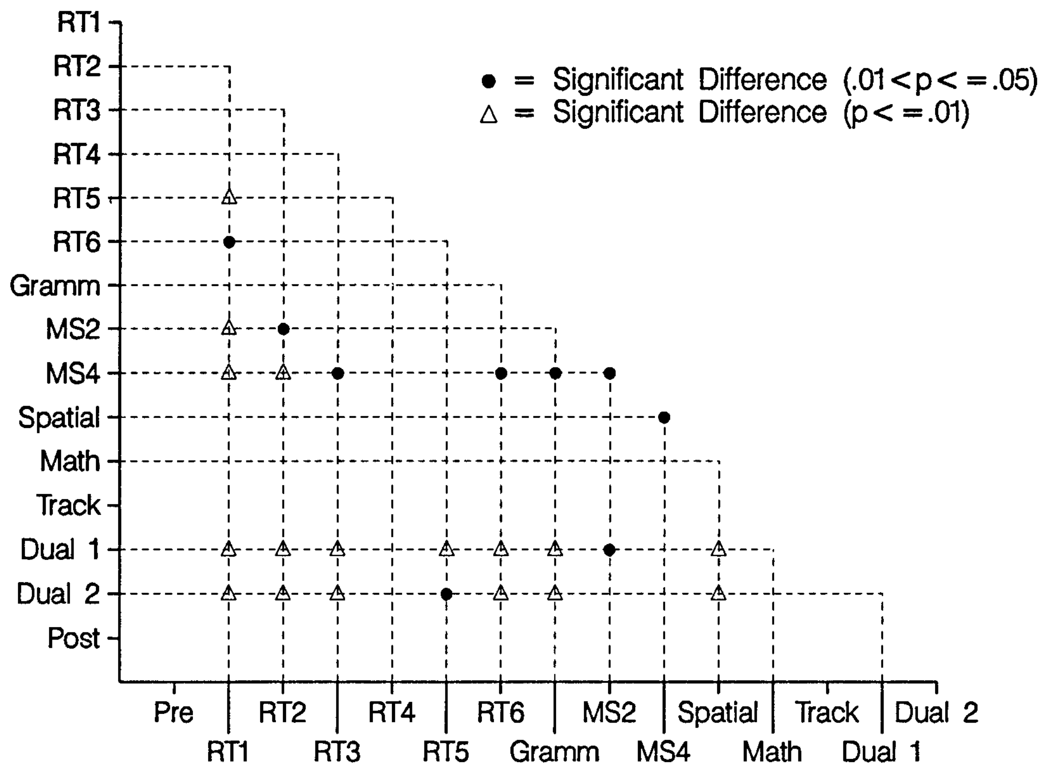


Figure 50. Top: Mean amplitude at Pz for N1 for STRES battery tasks for Session 2. Bottom: Matrix of significance of between task comparisons.

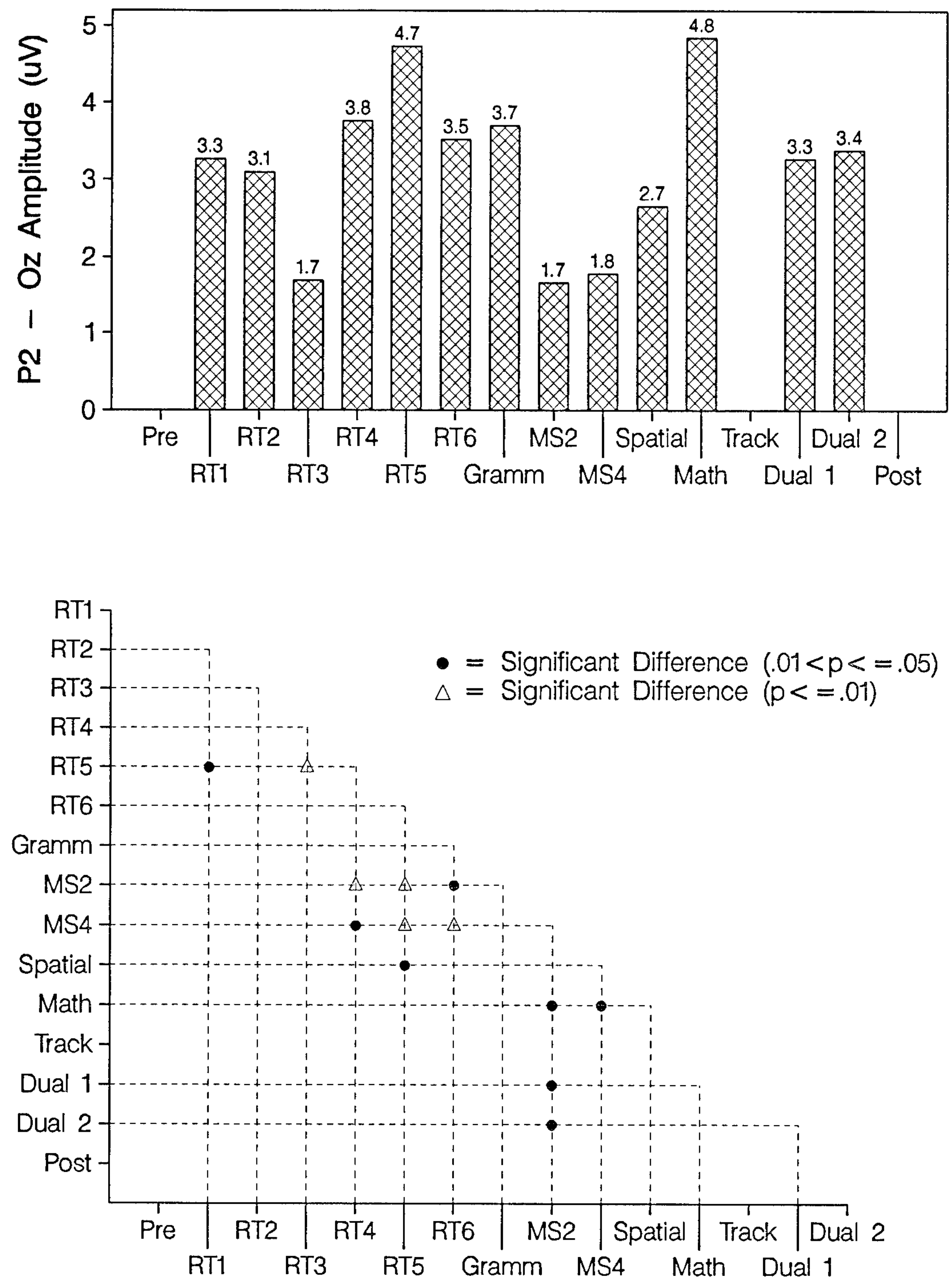


Figure 51. Top: Mean amplitude at Oz for P2 for STRES battery tasks for Session 2. Bottom: Matrix of significance of between task comparisons.

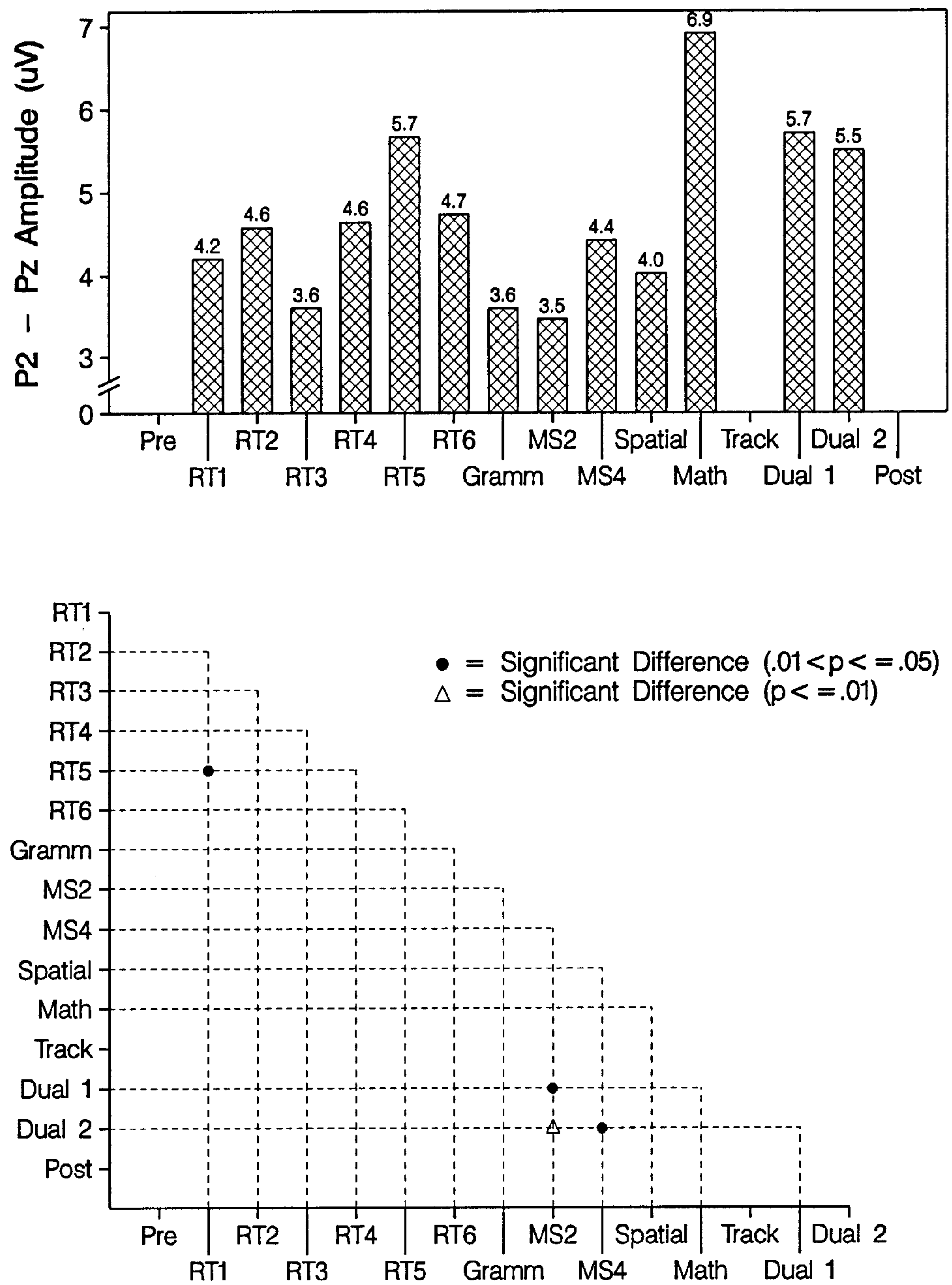


Figure 52. Top: Mean amplitude at Pz for P2 for STRES battery tasks for Session 2. Bottom: Matrix of significance of between task comparisons.

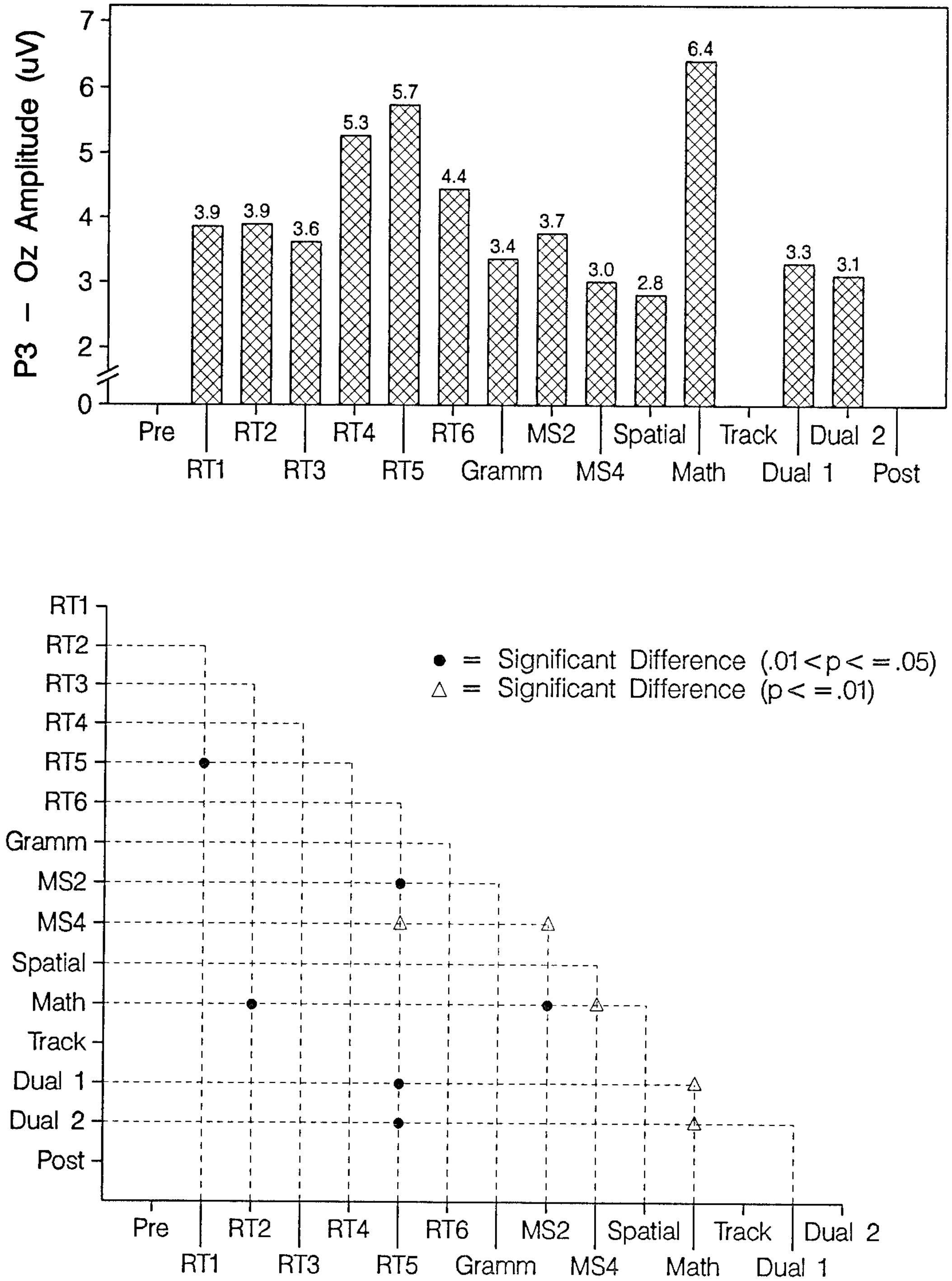
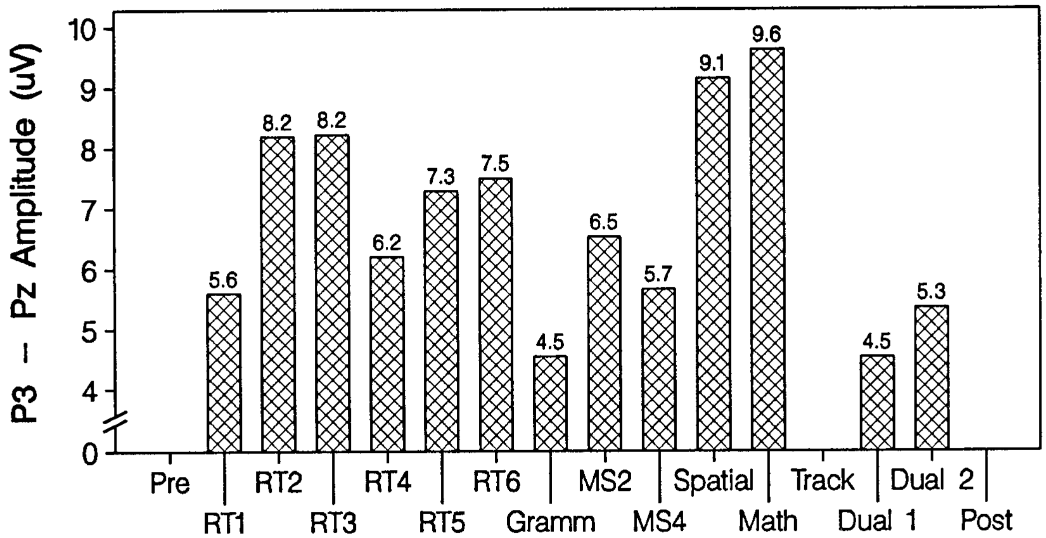


Figure 53. Top: Mean amplitude at Oz for P3 for STRES battery tasks for Session 2. Bottom: Matrix of significance of between task comparisons.



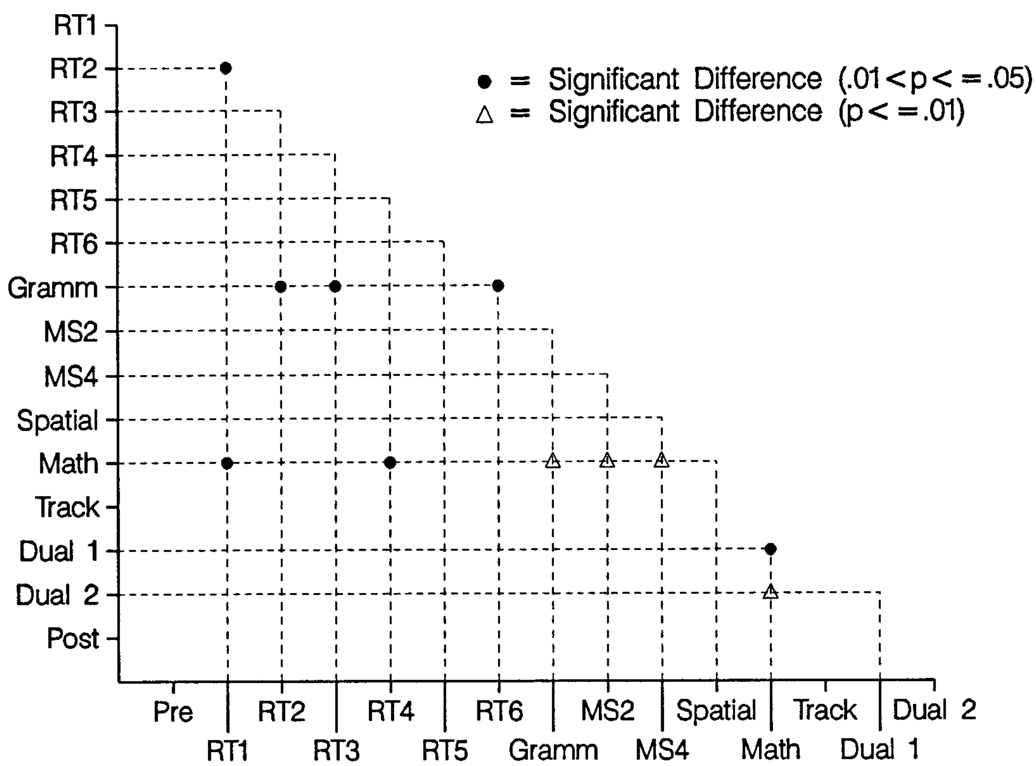


Figure 54. Top: Mean amplitude at Pz for P3 for STRES battery tasks for Session 2. Bottom: Matrix of significance of between task comparisons.

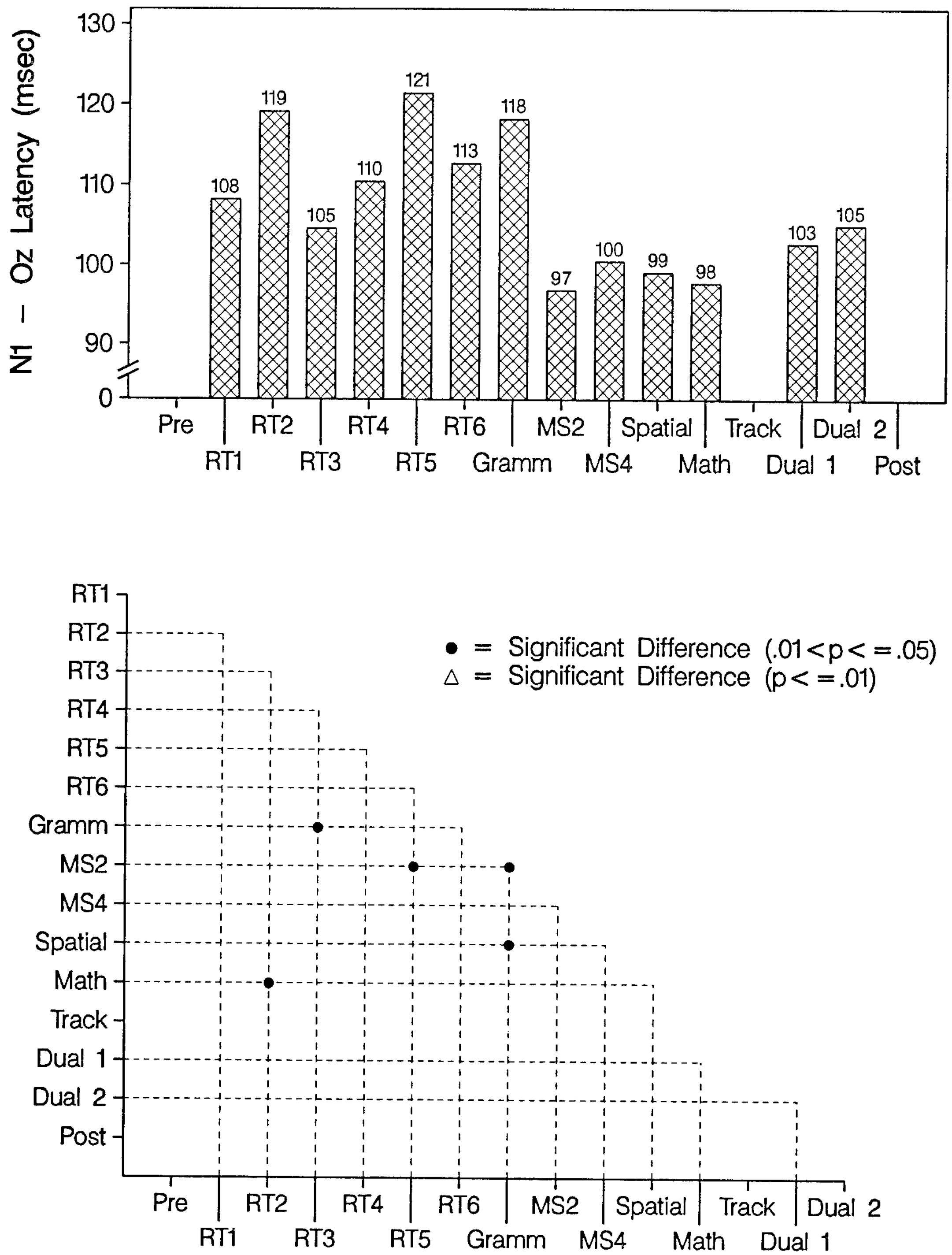


Figure 55. Top: Mean latency at Oz for N1 for STRES battery tasks for Session 2.
Bottom: Matrix of significance of between task comparisons.

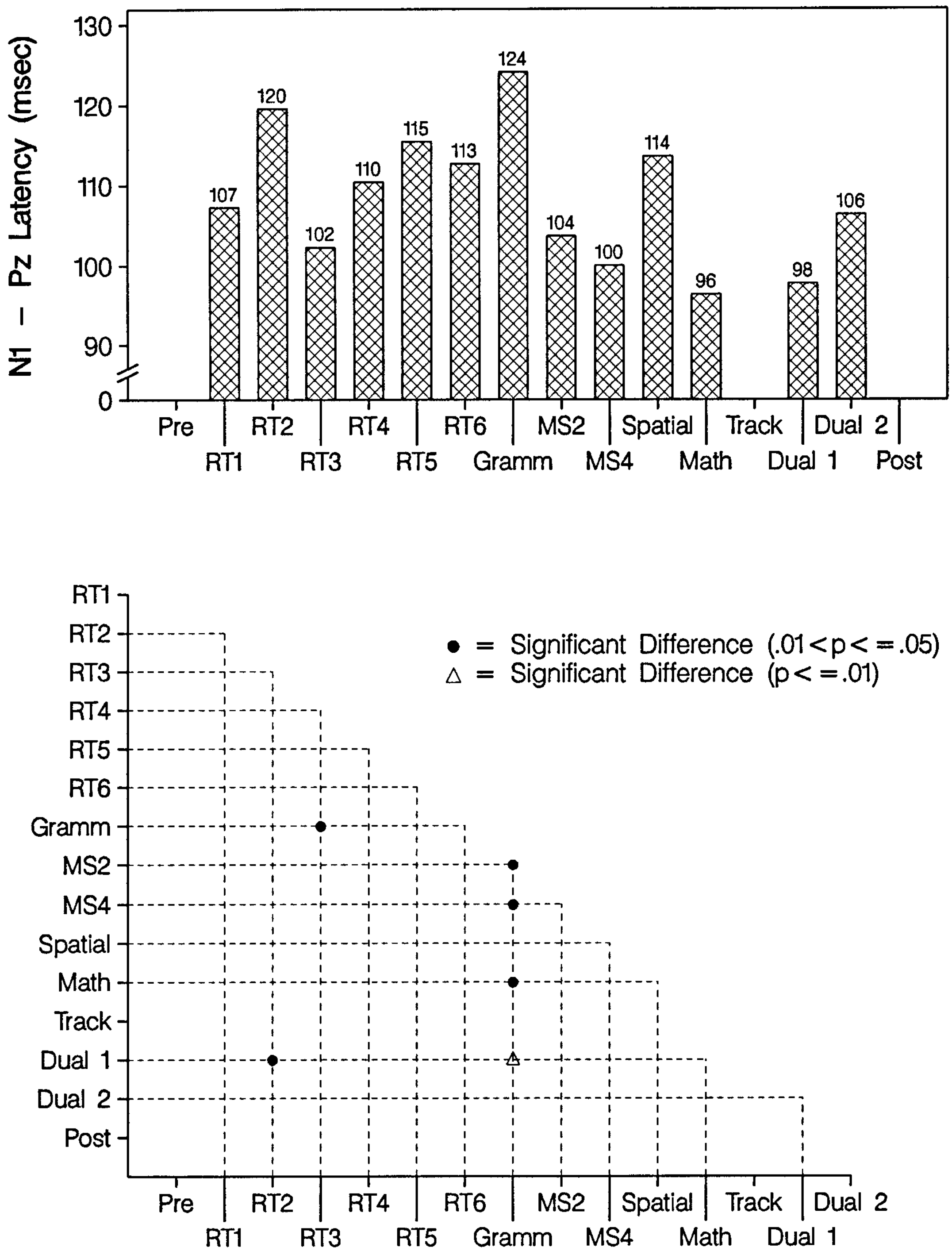
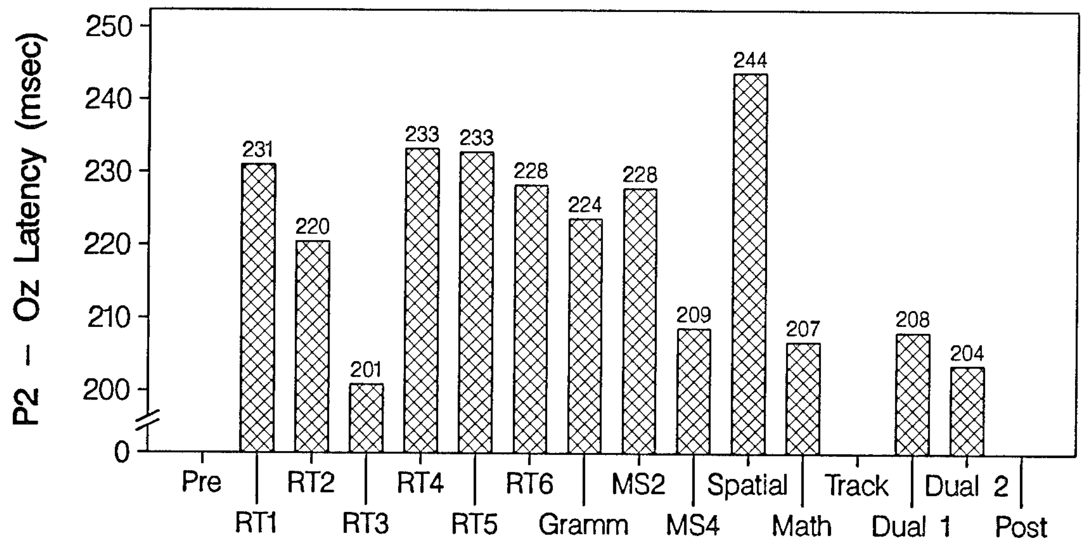


Figure 56. Top: Mean latency at Pz for N1 for STRES battery tasks for Session 2. Bottom: Matrix of significance of between task comparisons.



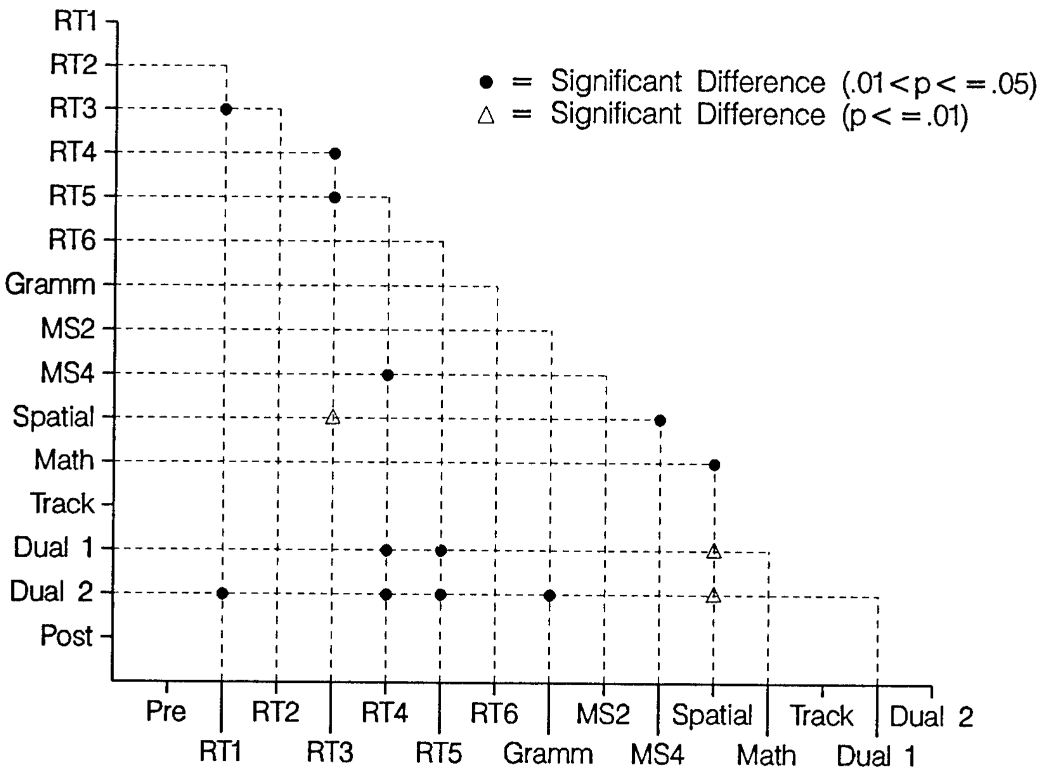
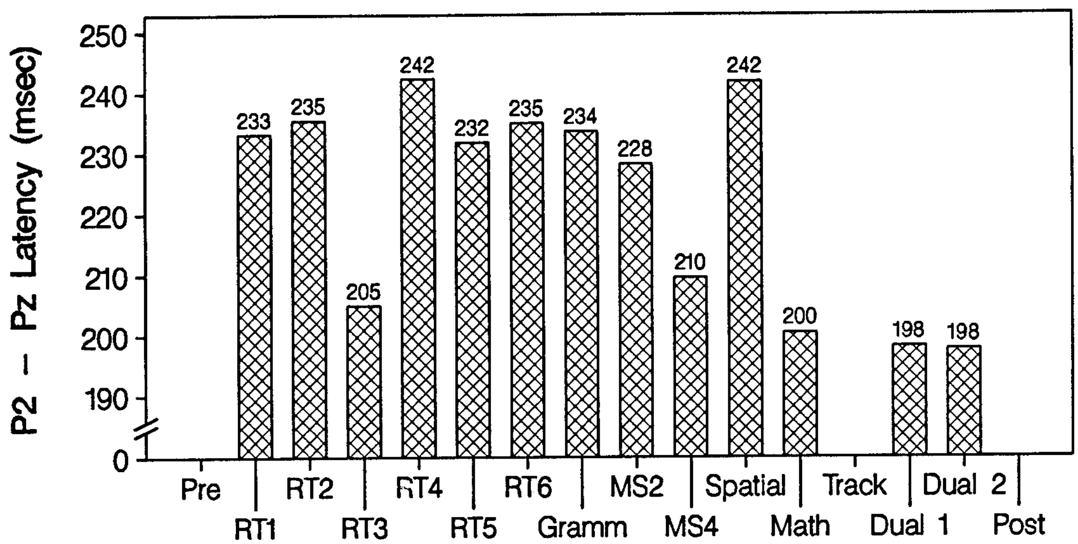


Figure 57. Top: Mean latency at Oz for P2 for STRES battery tasks for Session 2. Bottom: Matrix of significance of between task comparisons.



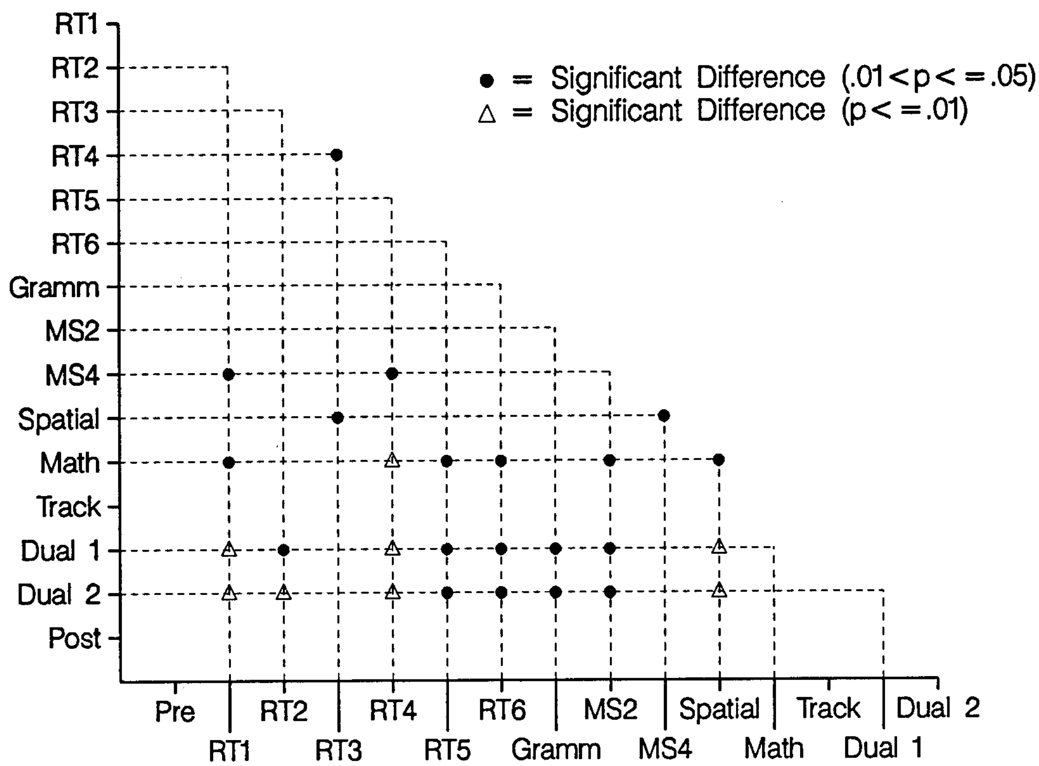


Figure 58. Top: Mean latency at Pz for P2 for STRES battery tasks for Session 2. Bottom: Matrix of significance of between task comparisons.

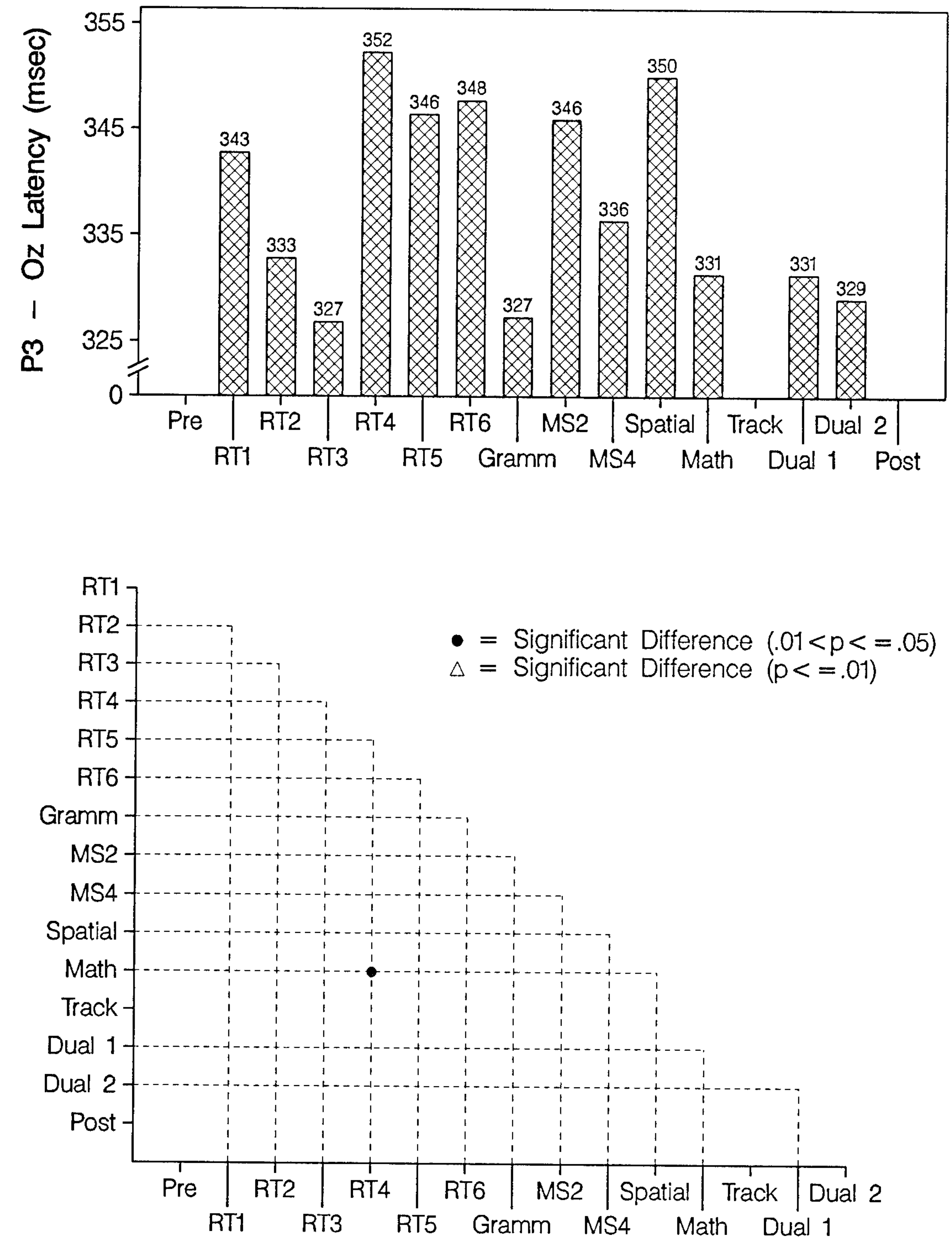


Figure 59. Top: Mean latency at Oz for P3 for STRES battery tasks for Session 2. Bottom: Matrix of significance of between task comparisons.

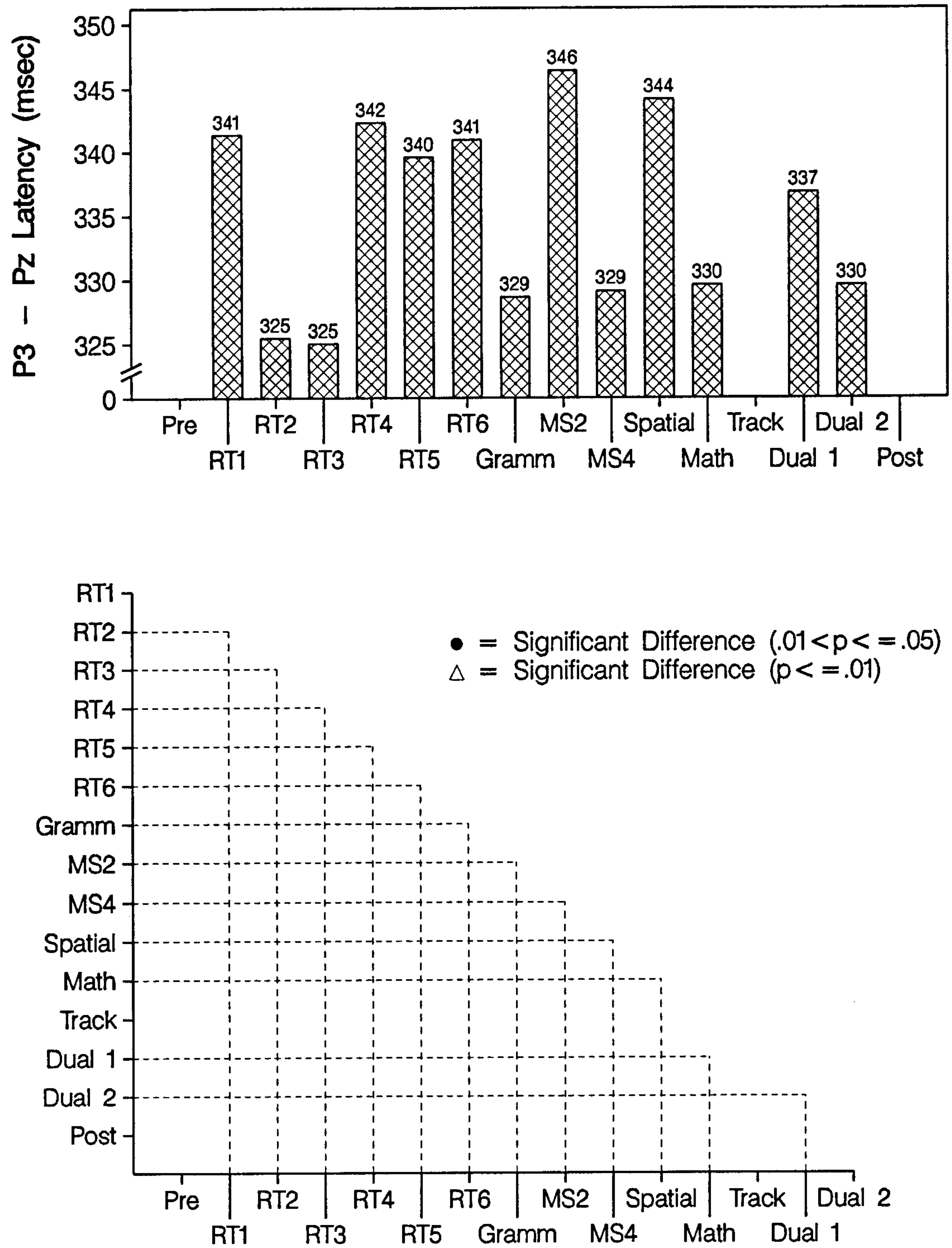
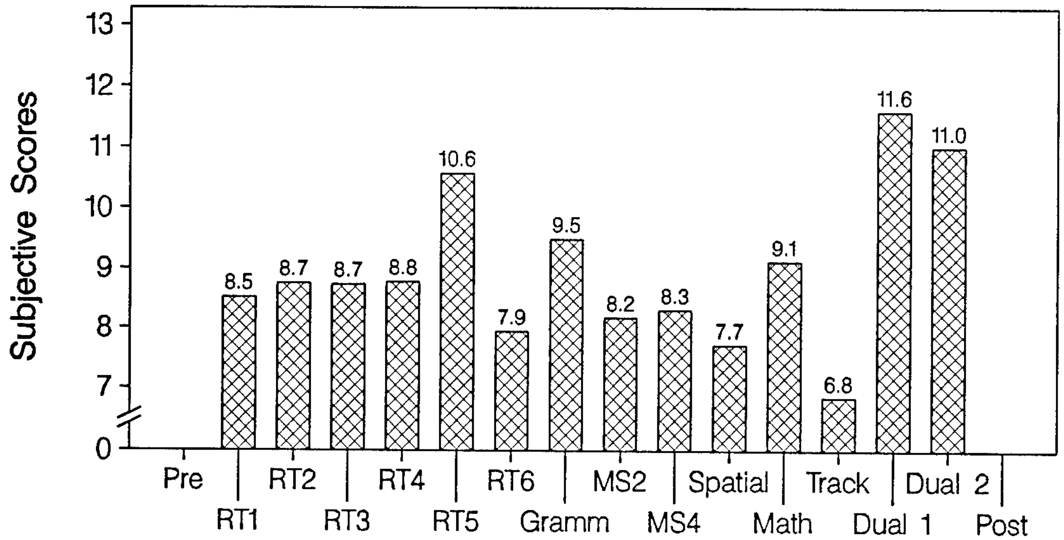


Figure 60. Top: Mean latency at Pz for P3 for STRES battery tasks for Session 2. Bottom: Matrix of significance of between task comparisons.



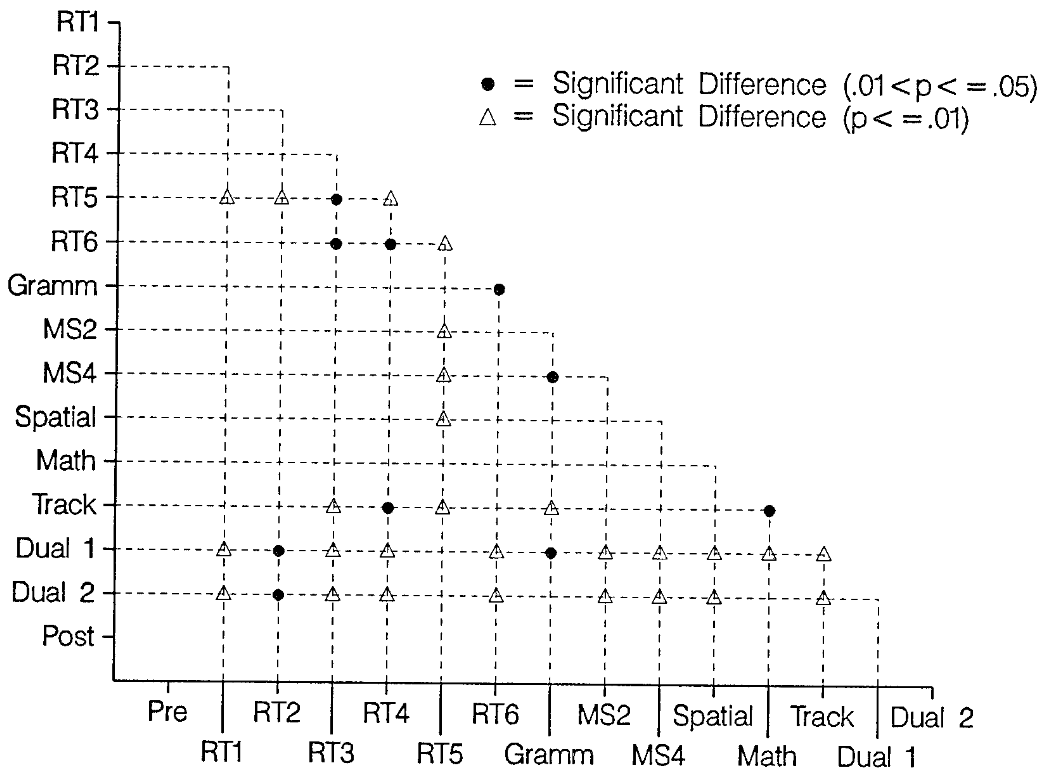


Figure 61. Top: Mean subjective (NASA–TLX) scores for STRES battery tasks for Session 2.
Bottom: Matrix of significance of between task comparisons.

DISCUSSION

This study sought to determine if there were decrements in performance and changes in physiological and subjective measures as a function of sleep loss. A second goal was to determine if the changes in these dependent measures would be overcome by one night's recovery sleep.

In contrast to many findings in the literature, the attempt to quantify performance decrements with one night's sleep loss was successful. Reaction times on STRES Battery tasks consistently increased with sleep deprivation and several of the Session 2 vs Session 4 reaction time comparisons were significant. Accuracy of responses decreased with sleep loss, and both this measure and reaction time recovered with one night of sleep. These performance decrements were seen for tasks representing all stages of cognitive processing, but especially for reaction time tasks. Also consistently affected was total RMS error for the tracking task with one night's sleep loss, under both single and dual-task conditions. In real-world situations which require tracking to be performed in conjunction with other tasks, a situation which would be analogous to this experiment's dual-task conditions, we should expect to see a decrement in performance with moderate levels of sleep deprivation.

A specific analysis of effects within the STRES Battery tasks can be seen in Figure 62. The number of times a significant physiological, performance, or subjective difference between Sessions 2 and 4 was generated for each of the STRES Battery tasks was counted, and this number was divided by the number of times it could have produced an effect (for instance, there would have been no opportunity for evoked potentials to be significant for the tracking task since they were not gathered for that task). Of all the STRES Battery tasks, the reaction time tasks produced the greatest number of physiological, performance, and subjective effects. It can be seen that in general the reaction time tasks, especially RT 3, RT 6, RT2 and RT 4, and MS 4 were

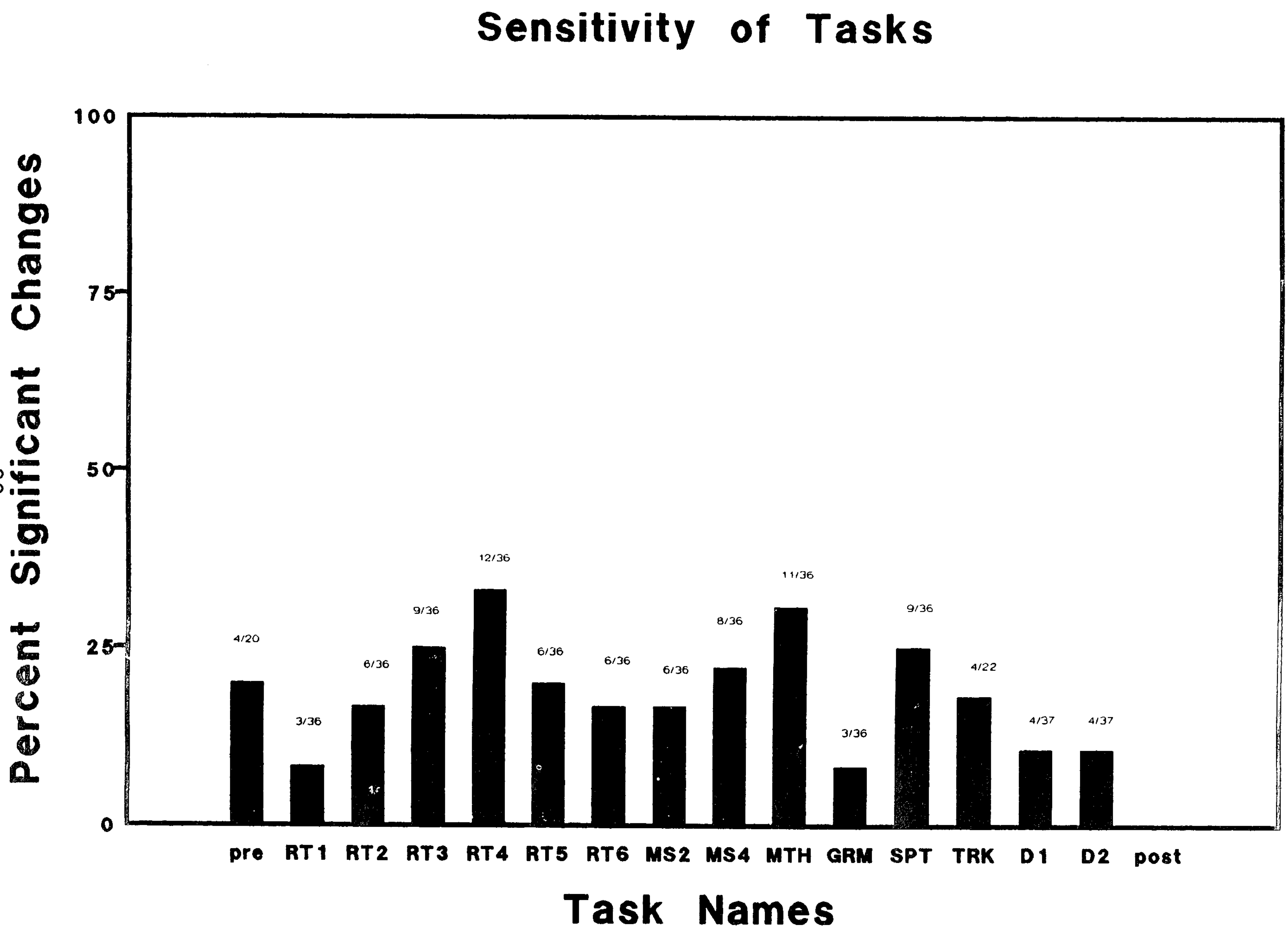


Figure 62. A frequency count of the number of times a STRES Battery task was associated with a significant Session 2 vs Session 4 difference in one of the dependent measures, converted to a percentage by dividing the

associated with the greatest number of significant results. The extrapolation of this finding is that, in the field, if there were minimal time and testing resources at hand to determine if there were a performance decrement attributable to sleep loss, a few tasks, for instance, the most productive reaction time tasks shown here, as well as the tracking task, combined with a measure of heart rate variability, could be administered, rather than the whole test battery.

These performance changes with just one night's sleep loss, and their subsequent recovery with one night's sleep, make it clear that there is a measurable decrement in processing at the input, central, and motor stages. The five different reaction time tasks were consistently affected by sleep deprivation. The performance decrements were consistent for these tasks, as was their recovery. Central processing (grammatical reasoning, mathematics, spatial processing, and the memory tasks) was affected as well, and the motor output resources (as shown in the RT 4, RT 5, and tracking task under single and dual conditions) showed a clear deficit.

One possible reason that this study was successful in finding performance effects of one night's sleep loss where others have not, might be attributable to the test battery which was employed. The STRES Battery includes tests that tax several processing resources, which would allow a deficit at any stage, input, central, or motor, to reach a level where it would be manifested in a changed reaction time or error score. Additionally, the experiment's methodology ensured that subjects were well trained on all the tasks before data were gathered, and tests were administered at the same time of day every day to avoid any confounds with circadian rhythm.

Physiological measures were also sensitive to one night's sleep loss. It should be noted that the STRES Battery tests are not equated for stimulus characteristics such as presentation duration, screen luminance, etc., all of which could influence physiological measures. Heart rate variability showed numerous significant increases between Sessions 2 and 4, especially in the high band. HRV has been shown to increase with declining attention (Kalsbeek, 1970), while heart rate does not. Since the high band of heart rate variability is thought to reflect momentary respiratory influences, it may be that sleep loss affected respiratory parameters not tested in this study. Several studies report reduced respiratory efficiency with sleep loss (increased duration of apneic events, Carscadon and Dement, 1985; reduced response to hypoxia, Cooper and Phillips, 1982). Plyley, Shephard, Davis, and Goode (1987) found a decrease of seven percent in oxygen consumption during 64 hours of sleep loss (due to a decrease in minute ventilation and hemodilution rather than a change in respiratory exchange ratio). Eye blink rate, and to a lesser extent, eye blink duration, increased after a night without sleep. The central nervous system measures were not as consistently affected by sleep loss as were the peripheral measures.

The subjective impressions of subjects about the difficulty of each of the STRES Battery tasks increased with sleep loss, and recovered following a night's sleep. This measure produced almost as many significant findings as any of the performance or physiological measures.

In order to summarize the usefulness of the many measures discussed here in terms of evaluating sleep loss effects, Figure 63 was developed. A frequency count of the number of times one of the peripheral physiological, performance, and subjective dependent measures showed a significant difference between Sessions 2 and 4 on any of the STRES Battery tasks was converted to a percentage by dividing the frequency count by the number of times that measures was taken (e.g., no performance measures during baselines, although physiological data were taken, and RMSE error gathered only during tracking). Heart rate variability in the high band stands out as being significantly affected by sleep loss under many task conditions; HRV-medium, reaction time, the variability of reaction time, and the subjective index produced about equivalent levels of significant results. It should be noted, though, that laboratory testing conditions may produce results that contrast to those taken under

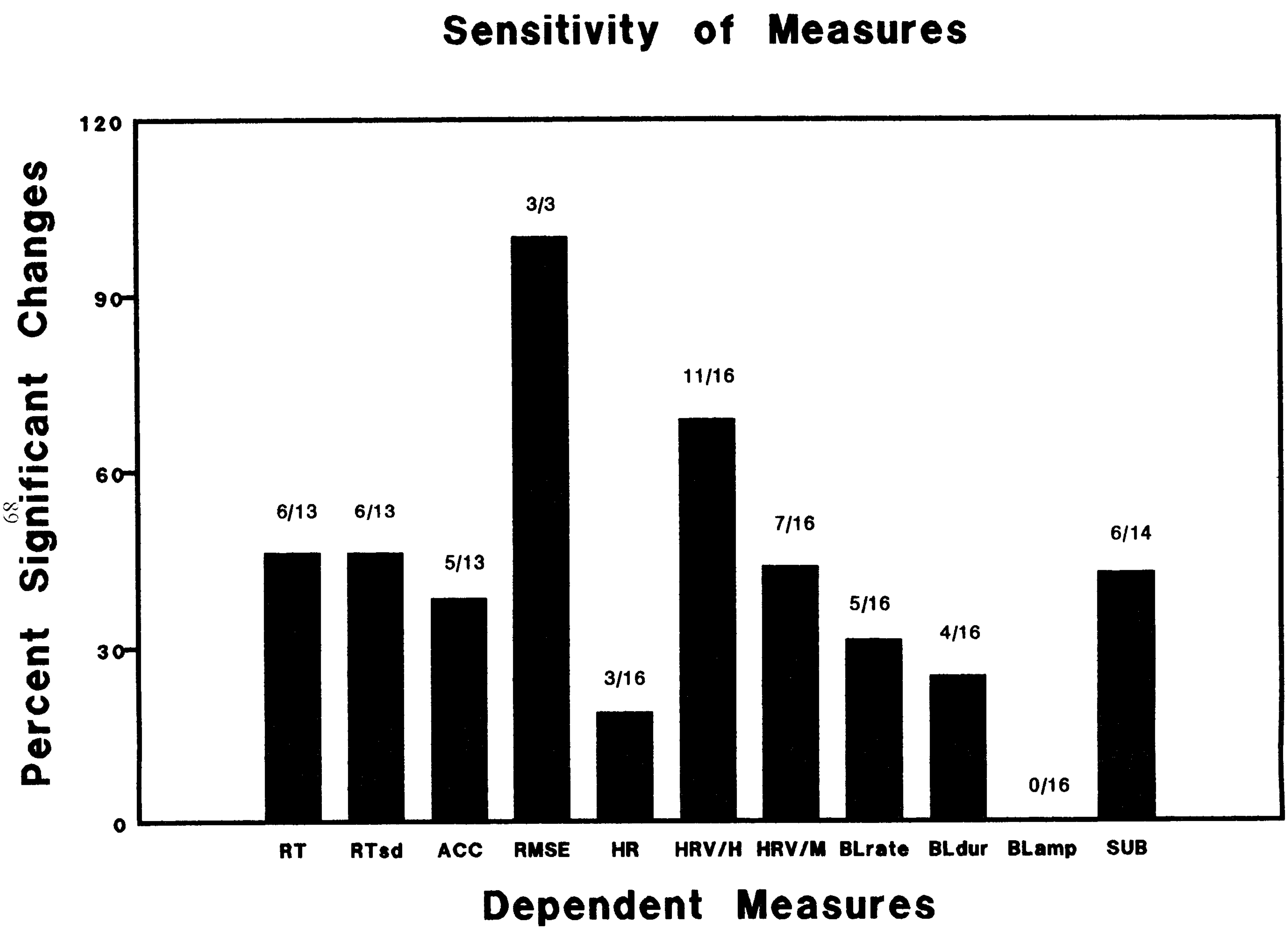


Figure 63. A frequency count of the number of times one of the dependent measures showed a significant difference between Sessions 2 and 4 on any of the STRES Battery tasks, converted to a percentage by dividing the frequency count by the number of times that measure was taken.

more real-world conditions; heart rate variability specifically may be differentially affected by lab versus real-world settings (Wilson, 1992). Note also that RMS error was collected only during the three tracking tasks and was significant in all cases.

The analyses which were performed within Session 2 over tasks for each of the dependent measures also permits examination of between-task differences under non-sleep deprived conditions. As physiological or subjective measures change over tasks, we can determine the relative requirements of these tasks. The changes reveal the sensitivity of the different physiological measures to task differences. Examination of which tasks produced significantly different physiological outcomes than other tasks tell us about these relative task requirements and how they affect physiological measures.

Heart rate and heart rate variability differences over tasks during Session 2 were due largely to a decreased heart rate and increased degree of variability during post-baseline testing. Decreased heart rate might be attributable to relaxation by the subject at the end of test battery administration and a decreased rate increases the opportunity for variability to occur. However, the decreases in heart rate for RT 4, Dual Task 1, and tracking were great enough to allow them to differ significantly from several other tasks. The blink parameters (rate, amplitude, and duration) showed differences (reduced rate, decreased duration) for tracking tasks, which are continuous and may have been among the most visually demanding tasks. The spatial and math tasks were associated with increased blink rate, as was MS 4 to a lesser extent. EEG differences occurred most often for the reaction time tasks, while EP changes were seen most frequently as a function of dual-task requirements. For the EEG analyses, RT 4 and RT 5 were associated with decreases in relative power in the alpha band at Oz and Pz while MS 4, math, tracking, and post-baseline showed increased relative power in this band. The mean theta power at Oz, on the other hand, showed significantly increased relative power during the RT 4 and grammatical reasoning tasks with significantly reduced relative power during the tracking task. It is interesting to note that the relative alpha and theta power at both Oz and Pz for tracking were significantly different from the Dual 1 and Dual 2 tasks which required tracking while performing a second task, memory search. Adding the central-processing memory task resulted in the changes in alpha and theta. Decreased alpha and increased theta during cognitive tasks have been previously reported (Lang, Lang, Kornhuber, Diekmann, and Kornhuber, 1988).

It is possible to explain some of the between-task physiological differences in terms of their perceived difficulty. EEG, for example relates well to subjective data. High relative power at theta at Pz for the dual tasks and grammatical reasoning is reflected in high subjective difficulty scores for those tasks, and the low relative theta power for tracking is associated with a perception that the tracking task is the easiest of the STRES Battery tasks. The reverse is seen in relative alpha power: high relative alpha occurs during the easy tracking task, and alpha is low for the dual tasks and grammatical reasoning.

This study reveals several key issues. The first is that moderate sleep deprivation does produce significant performance decrements. Specifically, it took subjects longer to make responses, and those responses were less accurate after a night without sleep. Performance recovered with one night's sleep. Such information is crucial to the planning of missions of extended duration, when normal sleep cycles are not possible, and in this context it is also important to note that the tracking task, under single and dual-task conditions, was consistently affected by sleep loss. Future testing might evaluate the usefulness of naps or pharmacologic agents, or, as a first step, might determine to what degree sleep cycles can be interrupted before the performance decrement is seen.

A second point is that the STRES Battery is a valid instrument to use in the detection of performance differences generated by one night's sleep loss. This ability makes the STRES battery a good choice for further sleep deprivation research in the laboratory as well as an excellent tool for the field in determining sleep loss effects. This battery can be administered in paper-and pencil or computer form and can be completed fairly quickly, making it practical in both the laboratory and applied settings.

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