

# A Quantitative Electroencephalographic Correlate of Sustained Attention Processing

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**Abstract** The objective of the present investigation was to develop a quantitative electroencephalographic measure (qEEG) that is sensitive and specific to changes in sustained human performance. A principal components analysis (PCA) was performed on the qEEG obtained from participants during a continuous performance test. Measures of sensitivity (proportion of correctly identified correct responses, or hits) and specificity (proportion of correctly identified incorrect responses, or misses) were calculated to assess the classification accuracy of each newly derived component. PCA solutions produced a right hemisphere component comprised of beta-wave activity measured from four unipolar sites (F8, C6a, C6, and T4) that appeared to be sensitive and specific to changes in human performance. Results provide evidence for the validity of a right hemisphere qEEG measure that is sensitive and specific to changes in sustained human performance. Consistent with the findings of previous research, the present findings implicate the right cerebral hemisphere in the sustained attention process.

**Keywords** Sustained attention · Vigilance · EEG · Right hemisphere · Performance · Principal component analysis · PCA · Factor analysis · FA

Despite recent advances in functional neuroimaging and other neurophysiological techniques very little research has been dedicated to the identification and the development

of functional measures that specifically index sustained attention processes within the human brain. Such measures would not only better inform future research on sustained attention—allowing for a better understanding of the sustained attention process—but might also be sensitive to discrete information processing impairments that are often associated with clinical disorders, including Attention Deficit Hyperactivity Disorder, HIV-1 related encephalopathy, mild cognitive impairment, traumatic brain injury, and dementia of the Alzheimer's type.

One exception to this trend has been the work of Arruda and colleagues (1996) who, through a series of published investigations, have developed a reliable and valid quantitative electroencephalographic (qEEG) measure that appears to index a sustained attention process with origins in the right cerebral hemisphere (Arruda et al., 1996; Arruda, Walker, Weiler, & Valentino, 1999). Comprised of beta-wave activity measured from the fronto-temporal (F8-T4) and temporal (T4-T6) regions, this multivariate measure has been demonstrated to be both a reliable and a valid index of sustained human performance during a continuous performance task (CPT; Arruda et al., 1999). Further, its topographic organization is consistent with current theoretical models of brain organization and function that suggest that the right cerebral hemisphere may mediate both arousal and the phasic selection of novel stimuli (Posner & Petersen, 1990; Tucker & Williamson, 1984).

Despite its psychometric strengths, the qEEG measure developed by Arruda and colleagues still possesses a number of limitations that reduce its usefulness as a theoretical and/or clinical diagnostic tool (Costa, Arruda, Stern, Somerville, & Valentino, 1997). For example, due to the instrument limitations in earlier studies conducted by this group EEG activity was sampled from a limited number of scalp sites using a bipolar recording montage that included only frontal,

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fronto-temporal, temporal, and temporo-occipital regions of the cerebral cortex. Given that previous research also has implicated central and parietal sites in the sustained attention process (Buchsbaum et al., 1990; Lewin et al., 1996; Paus et al., 1997; Sturm et al., 2004), it is important that the qEEG measure not be restricted to only those regions for which leads were available and that the measure be validated over a larger area of the cerebral cortex using a unipolar montage that possesses greater spatial resolution (Kahn, Weiner, Brenner, & Coppola, 1988).

Consequently, the purpose of the present investigation was to further develop the right hemisphere qEEG measure by collecting and analyzing the qEEG data obtained from an independent sample of participants using an expanded unipolar (referential) montage. Specific aims were to assess whether the expanded unipolar montage allowed for the identification of a unipolar measure (component) analogous to the original (right hemisphere) bipolar measure, and whether such a component would provide a more sensitive and specific index of right hemisphere mediated arousal. Below we present findings for the validity of a unipolar component that is comprised of beta-wave activity measured from frontal, central, and temporal sites that appears to be more sensitive and specific to changes in human performance than even the original bipolar component.

## Method

### Participants

Participants were 65 right handed undergraduate students (20 male; 45 female) whose ages ranged from 17 to 26 years, with the mean age of participants being 19.3 years ( $SD = 1.53$ ). All participants were in self-reported good health, with no previous history of neurological or psychiatric illness. Handedness was determined using a variation of the Edinburgh Handedness Inventory (Oldfield, 1971). Of the 65 students who participated in the present investigation, six (9.2%) were self-reported tobacco users, while 48 (73.8%) were self-reported caffeine users. The Institutional Review Board of the responsible institution approved the present investigation and informed consent was obtained from all participants prior to data collection.

### Instrumentation

Major instrumentation consisted of Neuroscan System 4 software, incorporating a dedicated “Stim” computer, which administered stimuli and recorded responses, and a separate “Scan” computer, which recorded the participant’s EEG. Coded synch pulses from the Stim computer corresponding to stimuli and responses were incorporated into the ongoing EEG recorded by the Scan computer, allowing analysis

of brain activity time-locked to specific events. EEG data were sampled at 500 Hz and band-passed .3–70 Hz ( $-12$  dB/octave + 60 Hz notch) through two 32-channel Synamp DC amplifiers.

A 64 channel Electrocap was positioned on the participant’s head according to standard procedures. The cap contained 58 active scalp electrodes, a ground electrode that was placed near Fz, reference electrodes that were attached to the ear lobes (A1 and A2), and three bipolar EOG electrode pairs that were placed superior, inferior, and lateral to each eye to monitor eye movement artifact. Two of the remaining electrodes were used to monitor left and right masseter muscle activity as recommended by Coburn and Moreno (1988). Muscle activity measured at both sites was analyzed in parallel with the EEG channels and used as marker variables to assist with the identification and the labeling of components. Trials contaminated by eye-movement artifact (EOG) were rejected on-line by an artifact rejection algorithm. All impedances were kept below 5 kohms.

### Procedure

Upon arrival each participant completed a demographic survey, which included items pertaining to the sex, handedness, race, tobacco use, and caffeine use of the participant. Once the demographic survey was completed, each participant was seated in a comfortable chair while electrodes were placed according to the Expanded International 10–20 System of electrode placement. Each participant was then instructed to listen, with eyes closed, to a computer-generated recording containing pseudo-randomly arranged letters of the alphabet presented binaurally through earphones (Valentino, Arruda, & Gold, 1993). Each participant was instructed to press a button using his or her right hand each time he/she heard a double-letter target (the same letter twice in a row). Stimuli were presented every 2,000 msec, and the total duration of the auditory CPT was 30 minutes. All auditory stimuli were clearly above threshold.

### Analyses

#### *Scan analyses*

EEG recordings from target trials were low pass filtered at 50Hz and epoched from  $-1024$  ms (approximately one second prior to target stimulus) to 0 ms (target delivery). Epochs were spline fit from 513 to 512 points and averaged in the frequency domain to extract (unipolar) absolute power values for each of the following five frequency bands: delta (0–3.90 Hz), theta (3.91–7.80 Hz), alpha (7.81–11.70 Hz), beta 1 (11.71–16.57 Hz), and beta 2 (16.58–24.37 Hz). Absolute power within each of the five frequency bandwidths was extracted for both correct trials (target hits) and for

**Table 1** Results of the two principal component analyses, which include the eigenvalues and the percentage of variance accounted for by each extracted component (bold)

Component	Rotation sums of squared loadings (Actual Correlation Matrix)			Rotation sums of squared loadings (Random Correlation Matrix)		
	Eigenvalue	%Variance	%Cumulative	Eigenvalue	%Variance	%Cumulative
1	<b>24.52</b>	<b>21.13</b>	<b>21.13</b>	<b>5.01</b>	<b>4.31</b>	<b>4.31</b>
2	<b>23.11</b>	<b>19.92</b>	<b>41.06</b>	<b>4.55</b>	<b>3.92</b>	<b>8.24</b>
3	<b>23.10</b>	<b>19.91</b>	<b>60.97</b>	<b>4.47</b>	<b>3.86</b>	<b>12.09</b>
4	<b>12.12</b>	<b>10.45</b>	<b>71.41</b>	<b>4.32</b>	<b>3.72</b>	<b>15.81</b>
5	<b>8.28</b>	<b>7.14</b>	<b>78.55</b>	<b>4.18</b>	<b>3.60</b>	<b>19.41</b>
6	3.66	3.16	81.71	4.11	3.55	22.96
7	3.33	2.87	84.58	4.00	3.45	26.41
8	2.19	1.89	86.46	3.98	3.43	29.84
9	2.09	1.80	88.26	3.65	3.14	32.98
10	1.74	1.50	89.76	3.53	3.05	36.03

*Note.* Only the first five components were extracted based upon the empirical decision rule associated with the parallel analysis procedure. The extraction method was principal component analysis.

incorrect trials (target misses or omissions) separately. Frequency bandwidths were selected to closely approximate those used by Arruda et al. (1996, 1999). For this reason, only beta-wave activity (beta 1 and beta 2) was considered.

In order to assess the classification accuracy and validity of a newly derived unipolar component, a right hemisphere bipolar component, similar to the one first described by Arruda et al. (1996), was also derived. The right hemisphere bipolar component was comprised of bipolar beta-wave activity (beta 1 and beta 2) obtained from F8-T4 and T4-T6. Bipolar channels were derived using the original unipolar recordings and a linear derivation procedure.

### Statistical analyses

A PCA was performed using a correlation matrix and the decision criteria established by Arruda et al. (1996) for extracting and retaining components obtained from a qEEG component solution. Component extraction, defined here as the process by which the number of components comprising a component solution is initially restricted, was based upon empirical and theoretical decision criteria. Consequently, components were extracted if they possessed eigenvalues greater than the eigenvalues produced by a random correlation matrix<sup>1</sup> (Horn's Parallel Analysis; Horn, 1965) and were meaningful with respect to the literature on sustained attention. To assess the meaningfulness of a candidate component, electrode sites previously implicated in the sustained attention process (Arruda et al., 1996; Arruda et al., 1999) were used as marker variables (sites) in the PCA. They included F8, T4, and T6. Finally, components were retained if they possessed three or more loadings with an absolute value greater than .60 (Anderson & Rubin, 1956; Velicer & Fava,

1987; Zwick & Velicer, 1986). All component solutions were orthogonally rotated using a VARIMAX rotation procedure prior to component extraction (Arruda et al., 1996).

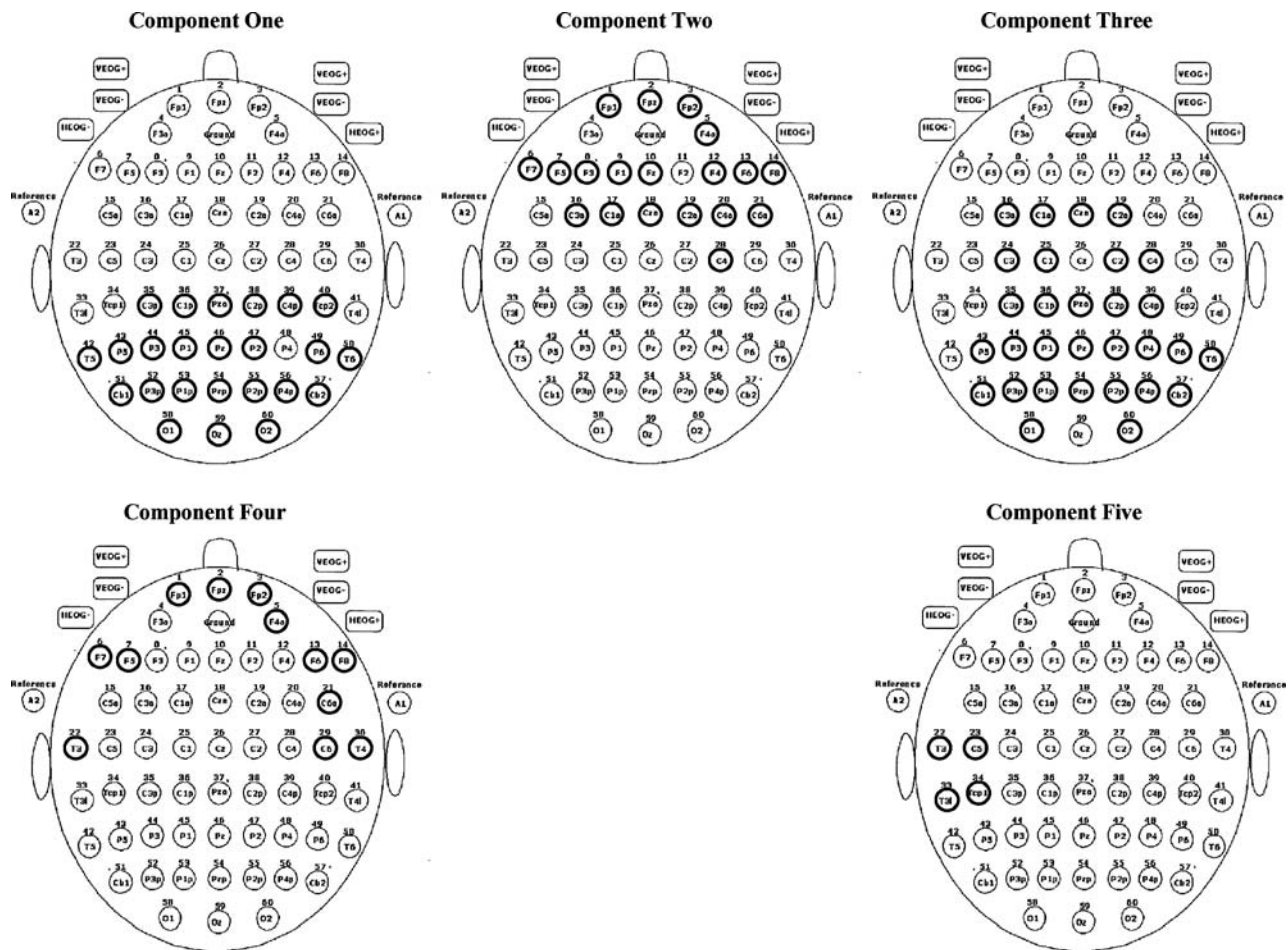
Measures of sensitivity (proportion of correctly identified correct responses, or hits) and specificity (proportion of correctly identified incorrect responses, or misses) were calculated from target trials for the newly derived (unipolar) component and compared with the sensitivity and specificity of the original (bipolar) right hemisphere component described by Arruda et al. (1996, 1999). Component scores were calculated using the scale score weighting procedure (Fava & Velicer, 1992) and cut-off scores for each component were chosen to maximize the combined sensitivity and specificity of each measure. The overall accuracy of each component was also assessed by combining the proportion of correctly identified hits and misses.

Differences in absolute beta power associated with correct (hits) and incorrect (misses) responses were also assessed using separate one-way, repeated measures analysis of variance (ANOVA) tests. Measures of treatment effect were also calculated.

### Results

Results of the PCA in conjunction with the Parallel Analysis procedure revealed a five component solution, which accounted for 78.55% of the variability in the original data set (Table 1). Of the five components initially extracted using the Parallel Analysis criterion, only one (i.e., component four) appeared meaningful with respect to the literature on sustained attention and it accounted for 10.45% of the variability in the original data set. More importantly, two of the three marker variables (F8 and T4) loaded highly on component four, with loadings greater than .60. In sum, the results of the PCA, which included the use of formal decision rules regarding the extraction and retention of components, produced a

<sup>1</sup>The random correlation matrix was constructed using an identical number of cases and variables.



**Fig. 1** Component model containing the five unipolar qEEG components. The five component solution was derived using absolute power in the beta-wave frequency bandwidth

single unipolar component (i.e., component four) that was comprised of activity from recording sites over the frontal (bilateral), the central (right), and the temporal (bilateral) regions (Fig. 1). Beta-wave activity measured from leads positioned over the left and right masseter muscle formed a single component that was uncorrelated to component four.

As can be seen in Table 2, the classification accuracy of the newly derived unipolar component (64%), which was comprised of beta-wave activity measured from Fp1, Fp2, Fp3, Fp4, F7, F5, F6, F8, C6a, T3, C6, and T4, was equivalent to the classification accuracy of the original bipolar component (64%), which was comprised of beta-wave activity measured from F8-T4 and T4-T6. However, upon closer inspection of the receiver operating characteristic (ROC) curves for the two components (Fig. 2), which were based upon all possible cut-off values, it became clear that the original bipolar component possessed an overall classification accuracy (63%) that was superior to the newly derived unipolar component (58%). Indeed, only the original bipolar component possessed an overall classification accuracy that was significantly greater than by chance (ROC = 50%),  $p < .05$ .

In an attempt to better understand the contributions made by the individual measures comprising the newly derived unipolar component, we subsequently calculated the sensitivity, specificity, accuracy, and ROC area associated with each measure comprising the new unipolar component (Table 3). As might be expected from its poor relative performance, eight of the 12 measures comprising the unipolar component failed to accurately predict correct and incorrect performance during the CPT and were at chance level ( $p > .05$ ). Further, of the eight measures that failed to accurately predict performance, four were measured from sites located over the left cerebral hemisphere. Of those four measures that did accurately predict performance ( $p < .05$ ), all were measured from sites located over the right cerebral hemisphere—a finding that is consistent with the cognitive neuroscience literature on sustained attention and arousal (Posner & Petersen, 1990). Further, a composite (i.e., component) of those four variables produced an overall classification accuracy (65%) that was even greater than the overall classification accuracies produced by either the original bipolar component (63%) or the newly derived (12 variable)

**Table 2** Sensitivity, specificity, and accuracy of the bipolar component, the twelve-variable unipolar component, and the four-variable unipolar component

	Absolute power (Mean ± SD)		Cut-Off	Sensitivity (%)	Specificity (%)	Accuracy (%)	ROC Area (%)
	Correct	Incorrect					
Bipolar Component	2.06 ± 1.20	1.54 ± 1.18	1.13	75	50	64	63*
Unipolar Component (12)	1.27 ± .58	1.13 ± .73	.65	91	31	64	58
Unipolar Component (4)	1.23 ± .52	1.01 ± .73	.58	95	35	68	65*

*Note.* The sensitivity and specificity values presented were based upon a single cut-off value that maximized the combination of sensitivity and specificity for each component. However, the area calculated to be under the receiver operating characteristic curve for each component was based on all possible cut-off values and should be considered as an overall measure of accuracy.

\*Significantly greater than a classification accuracy due to chance (ROC area of 50%),  $p < .05$ .

unipolar component (58%). In sum, the results of these analyses suggest that the most useful unipolar analogue of the original bipolar qEEG component (Arruda et al., 1996) may be a component comprised of beta-wave activity measured from four unipolar sites that include F8, C6a, C6, and T4.

Separate one-way, repeated measures ANOVA tests revealed statistically significant differences in mean absolute beta power between correct and incorrect responses for the original bipolar component,  $F(1, 47) = 4.92, p < .05$ , and for the newly derived four-variable component,  $F(1, 51) = 4.92, p < .05$ . No statistically significant difference in mean absolute beta power was found between the correct and incorrect responses for the newly derived twelve-variable component,  $F(1, 51) = 1.45, p > .05$ . Measures of treatment effect, as indicated by partial eta-squared ( $\eta^2$ ), for the original bipolar component, the newly derived four-variable component, and the newly derived twelve-variable component were .10, .09, and .03, respectively. In each case, the mean absolute beta power associated with correct responses or hits was greater than the mean absolute power associated with incorrect responses or misses.

**Discussion**

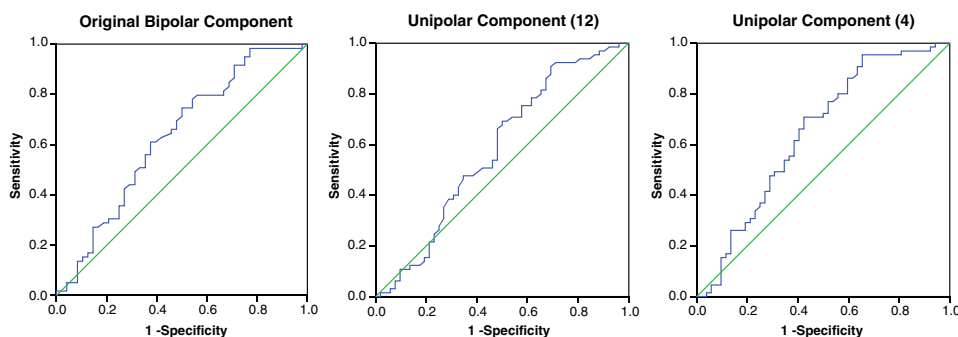
The purpose of the present investigation was to further develop a right hemisphere qEEG measure that is sensitive and specific to changes in sustained human performance during a CPT. Although previous attempts at developing

a neurophysiological measure of sustained human performance have produced solutions that have better informed research on the sustained attention process (Arruda et al., 1996; Arruda et al., 1999), such solutions have typically possessed a number of technical limitations that have reduced their usefulness—particularly as a clinical diagnostic tool (Costa et al., 1997).

The results of the present investigation provide evidence for the validity of a unipolar measure that is more sensitive and specific to changes in sustained human performance than the original bipolar measure derived by Arruda et al. in 1996. Comprised of beta-wave activity obtained from sites located over a broader region of the right cerebral hemisphere (i.e., frontal, central, and temporal), the unipolar measure has proven to be a more accurate predictor of both correct (hits) and incorrect (misses) responses measured during a CPT.

Consistent with findings from functional neuroimaging (Buchsbaum et al., 1990; Lewin et al., 1996; Paus et al., 1997; Sturm et al., 2004) and neurophysiological studies (Bearden, Cassisi, & White, 2004; Saletu et al., 2005), the findings from the present investigation further implicate the right cerebral hemisphere in the sustained attention processes. The results of this study also extend the findings of previous research by providing researchers with a non-invasive methodology by which an individual’s level of cortical arousal could be used to reliably predict his or her behavioral performance.

**Fig. 2** Receiver Operating Characteristic (ROC) Curves for the Original Bipolar Component, the Twelve-Variable Unipolar Component, and the Four-Variable Unipolar Component



**Table 3** Sensitivity, specificity, and accuracy of each measure comprising the twelve-variable unipolar component

	Cut-Off	Sensitivity (%)	Specificity (%)	Accuracy (%)	ROC Area (%)
Fp1	.59	85	31	61	56
Fpz	.53	86	35	63	56
Fp2	.55	88	31	62	56
F4a	.66	85	40	65	58
F7	.89	68	50	60	55
F5	.62	91	27	62	55
F6	.82	80	42	63	59
F8	.52	91	33	65	62*
C6a	.77	77	50	65	64*
T3	.54	82	42	64	58
C6	.61	85	40	65	63*
T4	.50	88	42	68	65*

Note. The sensitivity and specificity values presented were based upon a single cut-off value that maximized the combination of sensitivity and specificity for each component. However, the area calculated to be under the receiver operating characteristic curve for each measure was based on all possible cut-off values and should be considered as an overall measure of accuracy.

\*Significantly greater than a classification accuracy due to chance (ROC area of 50%),  $p < .05$ .

One possible application of this technology might be the use of cortical arousal measures to facilitate human-machine interaction, where detected changes in cortical arousal could be used to tailor machine processes and improve user performance. For example, a United States military research program, The Defense Advanced Research Projects Agency Augmented Cognition Program, has explored a variety of physiological measures to aid machine automation during cognitively demanding tasks (St. John, Kobus, Morrison, & Schmorrow, 2004). Augmented cognition works by assessing the user's physiological state and adjusting the task at hand by tailoring display information or assuming control over a subset of user tasks. The unipolar component identified in the present investigation has the potential to facilitate automation by providing the user with a more reliable and valid measure of cortical arousal.

Finally, given that measures of brain function may be more sensitive to early neuropathological changes than structural neuroimaging techniques (Feldman & Jacova, 2005), the findings of the present investigation suggest that the unipolar measure may serve as a more sensitive marker of early neuropathological changes that are associated with information processing impairments. This may be particularly true in the case of mild cognitive impairment where declines in cholinergic functioning often result in information processing impairments (Feldman & Jacova, 2005; Ralph, Patterson, Graham, Dawson, & Hodges, 2003).

## References

- Anderson, T. W., & Rubin, H. (1956). Statistical inference in factor analysis. *Proceedings of the Third Berkeley Symposium on Mathematics, Statistics, and Probability*, 5, 111–150.
- Arruda, J. E., Walker, K. A., Weiler, M. D., & Valentino, D. A. (1999). Validation of a right hemisphere vigilance system as measured by principal component and factor analyzed quantitative electroencephalogram. *International Journal of Psychophysiology*, 32, 119–128.
- Arruda, J. E., Weiler, M. D., Valentino, D. A., Willis, G., Rossi, J., Stern, R. A., Gold, S., & Costa, L. (1996). A guide for applying principal-component analysis and confirmatory factor analysis to quantitative electroencephalogram data. *International Journal of Psychophysiology*, 23, 63–81.
- Bearden, T. S., Cassisi, J. E., & White, J. N. (2004). Electrophysiological correlates of vigilance during a continuous performance test in healthy adults. *Applied Psychophysiology and Biofeedback*, 29, 175–188.
- Buchsbaum, M. S., Nuechterlein, K. H., Haier, R. J., et al. (1990). Glucose metabolic rate in normals and schizophrenics during the continuous performance test assessed by positron emission tomography. *British Journal of Psychiatry*, 156, 216–227.
- Coburn, K. L., & Moreno, M. A. (1988). Facts and artifacts in brain electrical activity mapping. *Brain Topography*, 1, 37–45.
- Costa, L., Arruda, J. E., Stern, R. A., Somerville, J. A., & Valentino, D. A. (1997). Asymptomatic HIV-1 infected women: A preliminary study of qEEG activity and CPT performance. *Perceptual and Motor Skills*, 85, 1395–1408.
- Fava, J. L., & Velicer, W. F. (1992). An empirical comparison of factor, image, component, and scale scores. *Multivariate Behavioral Research*, 27, 301–322.
- Feldman, H. H., & Jacova, C. (2005). Mild cognitive impairment. *The American Journal of Geriatric Psychiatry*, 13, 645–655.
- Horn, J. L. (1965). A rationale and test for the number of factors in factor analysis. *Psychometrika*, 30, 179–185.
- Kahn, E. M., Weiner, R. D., Brenner, R. P., & Coppola, R. (1988). Topographic maps of brain electrical activity—Pitfalls and precautions. *Biological Psychiatry*, 23, 628–636.
- Lewin, J. S., Fiedman, L., Wu, D., Miller, D. A., Thompson, L. A., Klein, S. K., Wise, A. L., Hedera, P., Buckley, P., Meltzer, H., Friedland, R. P., & Duerk, J. L. (1996). Cortical localization of human sustained attention: Detection with functional MR using a visual vigilance paradigm. *Journal of Computer Assisted Tomography*, 20, 695–701.
- Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, 9, 97–113.
- Paus, T., Zatorre, R. J., Hofle, N., Caramanos, Z., Gotman, J., Petrides, M., & Evans, A. C. (1997). Timerelated changes in neural systems underlying attention and arousal during the performance of an auditory vigilance task. *Journal of Cognitive Neuroscience*, 9, 392–408.
- Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience*, 13, 25–42.
- Ralph, M. A. L., Patterson, K., Graham, N., Dawson, K., & Hodges, J. R. (2003). Homogeneity and heterogeneity in mild cognitive impairment and Alzheimer's disease: A cross-sectional and longitudinal study of 55 cases. *Brain*, 126, 2350–2362.
- Saletu, B., Anderer, P., Saletu-Zyhljar, G. M., Gruber, D., Metka, M., & Huber, J. (2005). Identifying target regions for vigilance improvement under hormone replacement therapy in postmenopausal syndrome patients by means of electroencephalographic tomography (LORETA). *Psychopharmacology*, 178, 389–399.

- St. John, M., Kobus, D. A., Morrison, J. G., & Schmorow, D. (2004). Overview of the DARPA augmented cognition technical integration experiment. *International Journal of Human-Computer Interaction, 17*, 131–149.
- Sturm, W., Longoni, F., Fimm, B., Dietrich, T., Weis, S., Kemna, S., Herzog, H., & Willmes, K. (2004). Network for auditory intrinsic alertness: A PET study. *Neuropsychologia, 42*, 563–568.
- Tucker, D. M., & Williamson, P. A. (1984). Asymmetric neural control systems in human self-regulation. *Psychological Review, 91*, 185–215.
- Valentino, D. A., Arruda, J. A., & Gold, S. A. (1993). Comparison of QEEG and response accuracy in good vs poorer performers during a vigilance task. *International Journal of Psychophysiology, 15*, 123–133.
- Velicer, W. F., & Fava, J. L. (1987). An evaluation of the effects of variable sampling on component, image, and factor analysis. *Multivariate Behavioral Research, 22*, 193–210.
- Zwick, W. R., & Velicer, W. F. (1986). A comparison of five rules for determining the number of components to retain. *Psychological Bulletin, 99*, 432–442.