Published in final edited form as:

Doc Ophthalmol. 2013 February ; 126(1): 29–44. doi:10.1007/s10633-012-9357-7.

Objective Assessment of the Human Visual Attentional State

Kevin T. Willeford¹, Kenneth J. Ciuffreda, Naveen K. Yadav, and Diana P. Ludlam

SUNY State College of Optometry, Department of Biological and Vision Sciences, 33 West 42nd Street, New York City, NY 10036

Abstract

Primary objective—The purpose of this study was to develop an objective way to assess human visual attention using the alpha band component of the visual-evoked potential (VEP).

Design and methods—Six different attentional conditions were tested: eyes-open, eyes-closed, eyes-closed with backwards number counting, and three rapid serial visual presentation (RSVP) tasks. 18 visually-normal, young-adult subjects (ages 21 to 28 years) were tested binocularly at 1 meter for each condition on two separate days. The Diopsys™ NOVA-TR system was used to obtain the visual-evoked potential (VEP) and extracted alpha-wave and its related power spectrum. Additionally, the Visual Search and Attention Test (VSAT) was administered as a subjective measure of visual attention.

Results—Subjects exhibited significant decreases in power in the alpha band when comparing the eyes-closed to the eyes-open conditions, with power in the eyes-closed condition being, on average, twice as large. The response from the other four conditions did not reflect the differential attentional demands. The ratio of the power in the eyes-closed condition to the eyes open condition in the lower alpha frequencies (8–10 Hz) was found to be significantly correlated to the group's performance on the VSAT, especially the 10 Hz component.

Conclusions—An individual's ability to attenuate their alpha-component during visual processing may be a predictor of their visual attentional state. These findings solidify the role of the VEP alpha subcomponent as an objective electrophysiological correlate of visual attention, which may be useful in the diagnosis and treatment of human visual-attention disorders in the future.

Keywords

alpha wave; visual attention; visual evoked potential; VEP; visual cortex; visual attentional disorders; objective testing

Introduction

The visual-evoked potential (VEP) is the electrophysiological response that is extracted through signal averaging from visual stimulus-related activity recorded through the scalp and cranium over the occipital region near the inion [1]. The VEP has long been used as a clinical tool to determine if the primary afferent visual pathway is intact, as well as to assess

¹For all correspondence: ph. – 610-428-2704; fax - 212-938-5760; kwilleford@sunyopt.edu.

an individual's visual acuity [2,3,4]. Using high-contrast pattern-reversal stimuli, which consist of a black-and-white checkerboard pattern changing phase with constant mean luminance, the pattern VEP produces low variability of waveform both within an individual subject and across subjects [1]. The cortical activity is directly proportional to the number of pattern reversals (i.e., phase-changes). This allows the time-locked response to be extracted from the inherent noise to provide the VEP amplitude and latency.

Another electrophysiological response in the brain, the alpha wave, has a bandwidth of five Hz (8–13 Hz); it is a subcomponent of the overall VEP amplitude. It was first described by Berger [5]. Using the subject-dependent peak frequency as a dividing line, the alpha wave band can be separated into an upper ($[f_p]$ to $[f_p + 2]$) and two lower ($[f_p - 4]$ to $[f_p - 2]$ and $[f_p - 2]$ to $[f_p]$) sub-bands [6], where $[f_p]$ is defined as the frequency for which the power is maximum, e.g., 10 Hz. It is generally accepted that the alpha wave is related to thalamo-cortical attentional activity, with higher magnitude EEG power (μV^2) resulting from a large number of neurons discharging synchronously, and contrariwise with lower magnitude power resulting from desynchronization of those same neurons [6]. As such, the alpha wave amplitude (μV) is negatively correlated with metabolic function in the primary visual areas: high power is correlated with low metabolic function and vice versa [7]. It is most evident (i.e., highest power) in an eyes-closed condition of relaxed wakefulness [8]. However, it's amplitude is not simply dependent on visual stimulation [7]; it may be influenced by other factors such as visual imagery [9], vigilance [10], and visual attention [11,12,13]. Attenuation is observed in the lower alpha band with attentionally-demanding tasks, in the upper band with semantic processing [6], and the alpha band as a whole during visual processing [14,15,16]. The attenuation observed during the start of visual processing (from the eyes-closed to the eyes-open test condition) is of larger magnitude than the attenuation caused by increasing attentional load upon the eyes-open alpha rhythm [17].

Despite these experimental observations, there is still some degree of debate as to alpha's physiological meaning. Eye blinks and saccadic movements may have contaminated early measurements of alpha, but they can now be rejected as artifacts by conventional computer program software criteria [18]. Peak alpha frequency has also been shown to change relatively linearly with age [19], so using an age-matched sample is essential for measuring the desired bandwidth. Additionally, visuo-spatial attention is a complex process involving many areas of the brain composed of multiple cortical (e.g., frontal and parietal lobes) and subcortical (e.g., thalamus) components [20]. Lastly, when comparing results between studies, it is important to consider electrode placement on the scalp, as it will reflect activity of the underlying brain area [21]. Similar areas of the scalp should be used for comparative purposes at each test session.

The current study concentrated its focus on the alpha activity related to the primary visual cortex (V1). Past studies measuring attention-related alpha in the occipital lobe have suggested that the inability to attenuate during visual processing may relate to reading and learning problems [11,12]. William Grey Walter [22] was one of the earliest to note differences among individual's alpha wave characteristics. "R-type" people, named for their reactive alpha rhythms, comprise up to two-thirds of the population. They have an alpha wave that attenuates with visual processing, with it being largest with the eyes closed. "M-

type”, meaning “minus”, have consistently small alpha power, and they were described as using visual imagery to make decisions. Lastly, Walter described “P-type” individuals, namely those with persistently large alpha activity, poor reading skills, and an inability to sustain attention. Walter’s description of “P-types” reminded Ludlam [12] of some of his optometric patients who had been labeled as “reading or learning disabled”. Ludlam [12] described two cases in which children with alpha rhythms that did not exhibit attenuation could do so after conventional oculomotor-based optometric vision therapy, i.e., oculomotor rehabilitation, a subgroup of motor learning [23]. Along with the ability to now attenuate the alpha component, the children also demonstrated normal optometric clinical findings (e.g., enhanced fusional vergence ranges and dynamic accommodation) and improved academic performance, following therapy. The electrophysiological and behavioral improvements led Ludlam [12] to speculate that the attentionally-based alpha activation could represent the mechanism responsible for the success of vision therapy, at least in part, as imbedded in such therapy is a significant attentional aspect [23,24].

The connection between alpha reactivity and reading ability was also documented by Fuller [25]. He demonstrated that “minimally brain damaged”/learning-disabled (MBD/LD) children had significantly less alpha attenuation during both recall and addition, as well as word problem tasks. In contrast to Grey Walter [22] and Ludlam [12], Fuller [25] sought to isolate a pure attentional effect by having subjects close their eyes for all conditions. He quantified their ability to do so by calculating a ratio between the average EEG power during the attentionally demanding task (eyes-closed) and the average EEG power during the eyes-closed “rest” period; the lower the value below 1.00, the greater was their alpha attenuation ability. Eighty-percent of the MBD/LD sample demonstrated lack of attenuation capability in one or more of the three tasks; their average attenuation ratio across conditions was 1.01. In contrast, eighty-one percent of the attentionally-normal children sampled exhibited attenuation in all three conditions, and furthermore gave more correct responses. Their average attenuation ratio was 0.93, which was significantly lower than that of the MBD/LD sample. Fuller’s [25] paper provided a direct link between alpha attenuation and learning disabilities, as well as the first quantification of alpha-wave attenuation under the critical eyes-closed conditions, with its relation to attention.

The present study aimed to quantify the relationship between occipitally-based alpha under different attentional states in visually-normal young adults. The intent was to develop a simple clinical test for objective assessment of visual attention in normals, and in the future for special populations, including but not limited to, ADHD and mild traumatic brain injury (mTBI). The hypothesis is that the alpha band (8–13 Hz) can be used to detect and assess attentional state in the visually-normal, young-adult population.

Methods

Subjects

Eighteen (2 male, 16 female) visually-normal graduate and optometry students from the State University of New York, State College of Optometry, participated in the study. Ages ranged from 21 to 28 years old ($\bar{X} = 24$, $SEM = 0.46$). All (4 emmetropes, 16 myopes) had visual acuity of 20/20 at distance and near with refractive correction ($X_{RE} = -2.43$, $SEM =$

0.50; $X_{LE} = -2.97$, $SEM = 0.67$). None had a history of traumatic brain injury, ADHD, or any other attentional disorder. Exclusion criteria included the presence of amblyopia, strabismus, ocular or systemic disease, chronic or progressive neurological disease, cognitive deficit, or history of seizures. The Institutional Review Board (IRB) at the College of Optometry approved the study. Subjects provided their informed written consent.

Apparatus

To record and analyze the VEP data, the Diopsys™ NOVA-TR system (Diopsys, Inc., Pine Brook, New Jersey, USA) was used [26,27]. The system consists of a 17 H X 15 V degree display monitor for stimulus presentation, a monitor for use by the experimenter for data viewing, and a computer for stimulus generation and graphical display. The Diopsys™ system is available commercially and is approved by the FDA for both research and clinical use. A Diopsys Infant Amp 100 amplifier was used to increase the EEG signals. See Figure 1A for a picture of the Diopsys™ system.

Additionally, a 7" DoubleSight (DoubleSight Displays, Irvine, California, USA) DS-70U display monitor was used to present the rapid-serial visual presentation (RSVP) stimuli. A USB cable connected the display monitor to a computer containing the files. Microsoft PowerPoint was used to present the RSVP stimuli. The screen had a luminance of 2.4 cd/m² with a target contrast of 70%. A total of four stimuli were presented: either an "x" (31 min arc), a circle (38 min arc), a fire truck (31 min arc), or a boxed gift (31 min arc). See Figure 1B for a picture of the RSVP experimental apparatus.

Three Grass (Grass Technologies, Astro-Med Inc., West Warwick, RI, USA) gold cup electrodes, each (active, ground, and reference) 1 cm in diameter, were used to record the VEP. The Diopsys E1M105 impedance meter was used to measure impedance to assure adequate electrical output.

The Visual Search and Attention Test, or VSAT (© Psychological Assessment Resources, Inc), was administered to provide a standard clinical subjective measure of attention. The test involves a visual cancellation task that was developed by Trener et al. [28]. The VSAT is a norm-referenced measure of an individual's ability to scan accurately and sustain attention. It consists of two black-and-white, sixty-second practice tests, as well as two colored, sixty-second "real" tests. Each test contains ten horizontal rows of forty letters or symbols (thirty distractors, ten targets) that are either black, green, red, or blue text on white paper. The task was to cross out as many targets as possible in one minute. The test was scored by dividing the test field in half (twenty letters per side) and counting the number of correct cross-outs per side (right and left). The number of correct cross-outs was taken as the raw score. The normal values provided for the present sample ranged from the 17th to 95th percentile, with the 3rd through 16th percentiles suggestive of impairment and borderline performance. Test-retest reliability for the VSAT was found to be 0.95, using the Pearson product-moment correlation. Calculated sensitivity and specificity were 0.88 and 0.86, respectively [28].

Procedures

All subjects were provided a vision screening. This included distance visual acuity, contrast sensitivity at distance (6 m) and at 1 m, and a cover test at near (40 cm), all of which were normal [29]. In addition, each subject confirmed that they had received a comprehensive optometric vision examination within the past year, which included assessment of refractive status (distance and near), binocularity (e.g., amplitude of accommodation, positive and negative relative accommodation), and ocular health (e.g., dilated fundus examination). They were also queried regarding their general ocular and medical health, especially as related to seizures, brain injury, and attentional problems. No subject was taking any drugs or medications that could possibly affect attention.

The VEP amplitude, latency, and alpha-wave activity from the primary visual cortex were measured using one Grass gold active-channel electrode, one reference electrode, and one ground electrode. The electrode placement was slightly modified from the International 10/20 system [1], as suggested by the manufacturer. The active electrode was placed at the Oz position, 2.5 cm above the inion. The reference electrode was placed at the Fp1 position (approximately 10% of the distance from the nasion to the inion), and the ground electrode was positioned on the side of the forehead. The subject's skin was first cleaned with alcohol swabs, and then with NUPREP skin abrasive gel. The electrodes were positioned on the scalp with Ten 20 conductive gel. An elastic headband maintained the position of the electrodes on the scalp.

The impedance of each electrode was measured using the DIOPSYS impedance meter. Each electrode had to have an impedance of <5 kilo-ohms, per the standards of the International Society for Clinical Electrophysiology of Vision (ISCEV) [1]. The electrodes were then connected to the Diopsys Infant Amp 100 amplifier, with an amplification factor of 10,000 to increase the very small analog signals. An electronic band-pass filter (0.5-100 Hz) filtered any noise. An artifact detector in the provided software eliminated undesirable EEG signals produced by either blinks or saccadic gaze shifts.

After attaching the electrodes, subjects were instructed to place their head in a chinrest/headrest assembly, and then to gaze carefully at the center of the monitor. The chinrest was used to ensure that the subjects remained in the same position and viewing distance throughout testing. Seat height was adjusted so that the screen was at eye level and centered along the midline at a test distance of 1m. The VEP measurements were recorded with the subjects viewing binocularly with their distance refractive correction in place. Testing was performed in a darkened room (38 lux) with natural pupils. Subjects had rest periods between test conditions, as needed.

Data were obtained under six test conditions, with three trials per condition averaged over two sessions (for a total of six trials): eyes-open, eyes-closed, eyes-closed with number counting, a passive RSVP "gazing" task, and two "active" RSVP tasks. (1) In the eyes open condition, a standard full-field 64X64 (17 H X 15 V degree), black-and-white checkerboard pattern (20.59 min arc check size at 1 meter) was displayed on the monitor to determine the conventional baseline VEP. The checkerboard pattern had a Michelson contrast of 85% and a mean luminance of 64 cd/m². For each 20-second trial, the checkerboard pattern had a

temporal frequency of 2 Hz (four reversals per second). To maintain fixation and visual attention, a central, red, rotating central fixation target (0.5 deg diameter) was presented at all times. (2) In the eyes-closed condition, subjects closed their eyes, relaxed, and imagined that they were staring straight ahead where the central red fixation target had been presented. Additionally, subjects were instructed to “clear their mind” and sit back in the chair to make themselves “completely comfortable” to elicit maximum alpha wave activity [8]. 30–60 seconds were allowed before the data collection to ensure adequate time for such relaxation. (3) In the third condition, subjects kept their eyes closed as in the second condition, but now performed mental arithmetic; namely, the serial sevens subtraction test [30]. They silently counted backwards in decrements of seven, starting from 100, 96, and then 94 for the three trials, respectively, to prevent memorization of the number sequence. The subjects were then provided a short rest period, while the RSVP test conditions were being organized.

The last three RSVP conditions (4–6) were counterbalanced using a balanced latin square design [31], so that every condition followed all of the others at least once. For all RSVP conditions, a visual oddball paradigm was used [32]. The oddball paradigm involves high probability targets, which are intermixed with low probability targets that the subject must identify. The targets were presented for 750 ms with an intervening 250 ms blank period. The low-probability targets appeared either four (0.20 probability), five (0.25), or six (0.35) times to prevent prediction, with 20 total presentations per trial. They were pseudo-randomly distributed throughout trials, so that each occurred the same number of times across the entire experiment. The order of appearance was also pseudo-randomly distributed within trials, so that the stimuli did not appear more than three times consecutively. Either the “x” (distractor) or the circle (target) were presented on the DoubleSight monitor for the fourth and fifth conditions. The sixth RSVP condition included stimuli with more visual detail: either a fire truck (distractor) or the boxed gift (target). Each target appeared on the screen in a preview before the actual RSVP test condition to familiarize the subject with the specific image. All images were presented in the center of the screen, which was placed at a test distance of 1m along the midline. In the RSVP passive gaze condition (4), subjects were instructed to “just gaze” at the stimuli flashing on the screen. They were not asked to discriminate between the distractor and target. In the last two conditions (5, 6), subjects were instructed to discriminate between a distractor stimulus and the target stimulus. Subjects counted silently, and then verbalized afterwards the number of targets they had counted.

After the first session, subjects completed the VSAT per the manual instructions [28]. They were required to identify the red, green, and blue strips on the front of the test to ensure that they could discriminate the colors. Next, they completed practice tasks on the front of the test. For each of the four following tests (two practice, two real), they were provided the same instructions: scan from right-to-left or left-to-right, whichever is more comfortable. Subjects were informed to continue with the task, even if they believed to have made a mistake, and to feel free to go back if they believed to have missed an object. Lastly, they were instructed to “perform the task as fast as you can.”

Data Analysis

Data were analyzed using GraphPad Prism software. The difference in amplitude (microvolts, μV) between the N75 and P100 components was taken as the VEP amplitude (delta). The N75 and P100 latencies were also recorded. Alpha-wave characteristics were analyzed using Fourier transformation and power spectrum [33]. Peak frequency (f_p) was calculated using the equation provided by Klimesch [6] to ensure that all subjects had a similar alpha bandwidth. Lower and upper limits were also calculated as recommended by Klimesch [6]. The lower band is subdivided into two additional sub-bands, lower-1 ($[f_p - 4]$ to $[f_p - 2]$) and lower-2 ($[f_p - 2]$ to $[f_p]$). The upper band is defined as having frequencies from $[f_p]$ to $[f_p + 2]$. For the current study, the alpha attenuation ratio was defined as the alpha power (μV^2) during the eyes-closed condition divided by the alpha power during the eyes-open condition [$\text{AAR}_{2:1}$]; $\text{AAR}_{2:1}$ values greater than 1 suggest attenuation, as the alpha power is larger when eyes are closed. A second ratio, the $\text{AAR}_{3:2}$, was defined as the alpha power during the eyes-closed number counting condition divided by the power during the eyes-closed condition. Similar to Fuller's [25] calculations, for the $\text{AAR}_{3:2}$ ratio, values less than 1 suggests attenuation, as the alpha power is smaller when doing mental tasks.

The coefficient of variation ($\text{CV} = \sigma/\mu$) was used to assess repeatability of the measures taken [34]. It represents the intra-individual variability in a parameter [35]: the smaller the value, the greater the repeatability. Values for the VEP amplitude and latency were derived automatically with a cursor on the screen, with a resolution of $\sim 0.1 \mu\text{V}$ and 0.04 msec, respectively. The power spectrum values were read directly from the display screen, with a resolution of approximately $1 \mu\text{V}^2$.

Results

VEP Analysis: Group Data

Group mean parameters of the visual-evoked potential were analyzed. N75 latency ranged from 71.52 ms to 82.38 ms ($\bar{X} = 77.46$, $\text{SEM} = 0.62$), P100 latency ranged from 99.95 ms to 109.84 ms ($\bar{X} = 104.10$, $\text{SEM} = 0.68$), and VEP amplitude ranged from 7.81 μV to 31.10 μV ($\bar{X} = 18.27$, $\text{SEM} = 1.80$). All were within normal limits per our laboratory system and standards, as well as those of others under similar stimulus conditions (e.g., Chiappa [36]). The VEP information was reviewed to assure its normalcy before assessing the alpha component.

Power Spectrum Analysis: Group Data

The group mean power spectrum results across all 6 conditions are presented in Figure 2. A one-way ANOVA for the factor of power was significant [$F(5, 102) = 5.70$, $p = 0.0001$]. Tukey's multiple comparison post-hoc test revealed that the following individual comparisons were significant: 9 Hz vs. 13 Hz, 10 Hz vs. 13 Hz, and 11 Hz vs. 13 Hz (all $p < 0.05$). Across all six conditions, 10 Hz had the largest power ($\bar{X} = 17.80 \mu\text{V}^2$, $\text{SEM} = 1.44$), followed by 11 Hz ($\bar{X} = 16.67 \mu\text{V}^2$, $\text{SEM} = 1.31$), and then 9 Hz ($\bar{X} = 16.05 \mu\text{V}^2$, $\text{SEM} = 1.51$). Individual subject peak frequencies ranged from 10.07 Hz to 10.54 Hz ($\bar{X} = 10.33$ Hz, $\text{SEM} = 0.03$).

Power Spectrum Analysis: Group Data for Individual Frequencies

The group mean results were then analyzed using a one-way ANOVA for each frequency comparing conditions 1 through 6. The post-hoc results are presented in Table 1. Group mean alpha attenuation ratios are presented in Table 2. The mean alpha attenuation ratios for each subject and frequency, along with their respective coefficient of variation values, are presented in Table 3. Details for each power spectrum frequency are described below for the significant frequencies.

8 Hz: The one-way ANOVA revealed significant differences between conditions [$F(5, 102) = 2.99, p = 0.0146$]. Tukey's multiple comparison post-hoc test revealed a significant difference only between conditions 2 and 5 ($p < 0.05$). Analysis of each subject's $AAR_{2:1}$ showed that 11 subjects exhibited attenuation when comparing the eyes-closed to the eyes-open condition ($X = 1.51, SEM = 0.28$). Analysis of each subject's $AAR_{3:2}$ revealed that 12 exhibited a modest degree of attenuation comparing the eyes-closed number counting to the eyes-closed condition ($X = 0.98, SEM = 0.08$).

9 Hz: The one-way ANOVA revealed significant differences between conditions [$F(5, 102) = 6.30, p < 0.0001$]. Tukey's multiple comparison post-hoc test revealed significant differences between the following conditions: 1 and 2, 1 and 3, 2 and 4, 2 and 5, 2 and 6, and 3 and 5 (all $p < 0.05$). Analysis of each subject's $AAR_{2:1}$ showed that 17 subjects exhibited some degree of attenuation when comparing the eyes-closed to the eyes-open condition ($X = 1.847, SEM = 0.19$). Analysis of each subject's $AAR_{3:2}$ revealed that 11 exhibited a modest degree of attenuation comparing the eyes-closed number counting to the eyes-closed condition ($X = 0.95, SEM = 0.07$).

10 Hz: The one-way ANOVA revealed significant differences between conditions [$F(5, 102) = 11.10, p < 0.0001$]. Tukey's multiple comparison post-hoc test revealed significant differences between the following conditions: 1 and 2, 1 and 3, 2 and 4, 2 and 5, 2 and 6, 3 and 4, 3 and 5, and 3 and 6 (all $p < 0.05$). Analysis of each subject's $AAR_{2:1}$ showed that 16 subjects exhibited attenuation when comparing the eyes-closed to the eyes-open condition ($X = 2.17, SEM = 0.26$). Analysis of each subject's $AAR_{3:2}$ revealed that 14 exhibited a modest degree of attenuation comparing the eyes-closed number counting to the eyes-closed condition ($X = 0.87, SEM = 0.07$).

11 Hz: The one-way ANOVA revealed significant differences between conditions [$F(5, 102) = 12.08, p < 0.0001$]. Tukey's multiple comparison post-hoc test revealed significant differences between the following conditions: 1 and 2, 1 and 3, 2 and 4, 2 and 5, 2 and 6, 3 and 4, 3 and 5, and 3 and 6 (all $p < 0.05$). Analysis of each subject's $AAR_{2:1}$ showed that 17 subjects exhibited attenuation when comparing the eyes-closed to the eyes-open condition ($X = 2.93, SEM = 0.75$). Analysis of each subject's $AAR_{3:2}$ revealed that 9 exhibited a modest degree of attenuation comparing the eyes-closed number counting to the eyes-closed condition ($X = 1.06, SEM = 0.06$).

12 Hz: The one-way ANOVA revealed significant differences between conditions [$F(5, 102) = 5.61, p < 0.0001$]. Tukey's multiple comparison post-hoc test revealed significant

differences between the following conditions: 1 and 2, 2 and 4, 2 and 5, 2 and 6, and 3 and 7 (all $p < 0.05$). Analysis of each subject's $AAR_{2:1}$ showed that 13 subjects exhibited attenuation when comparing the eyes-closed to the eyes-open condition ($\bar{X} = 1.57$, $SEM = 0.21$). Analysis of each subject's $AAR_{3:2}$ revealed that 11 exhibited a modest degree of attenuation comparing the eyes-closed number counting to the eyes-closed condition ($\bar{X} = 0.99$, $SEM = 0.11$).

13 Hz: The one-way ANOVA revealed significant differences between conditions [$F(5, 102) = 4.55$, $p = 0.0009$]. Tukey's multiple comparison post-hoc test revealed significant differences between the following conditions: 1 and 2, 2 and 4, 2 and 5, and 2 and 6 (all $p < 0.05$). Analysis of each subject's $AAR_{2:1}$ showed that 16 subjects exhibited attenuation when comparing the eyes-closed to the eyes-open condition ($\bar{X} = 1.78$, $SEM = 0.21$). Analysis of each subject's $AAR_{3:2}$ revealed that 12 exhibited a modest degree of attenuation comparing the eyes-closed number counting to the eyes-closed condition ($\bar{X} = 0.87$, $SEM = 0.06$).

VSAT

Raw scores on the VSAT ranged from 135 to 199 ($\bar{X} = 167.39$, $SEM = 4.96$). The raw scores were converted to percentile scores, which ranged from the 11th percentile to the 95th percentile ($\bar{X} = 52.61$, $SEM = 29.32$). All subjects scored above the 2nd percentile/abnormal range; three scored in the borderline range (11th, 12th, and 16th percentile). However, these three borderline subjects did not have attenuation ratios that differed significantly from the top three performing subjects (t test, $p = 0.14$).

Eyes-Closed Alpha Power: Correlation with VSAT

Linear regression analysis was used to compare the alpha power in the eyes-closed condition at each frequency to the respective VSAT percentile score for each subject. Results are given below for the significant frequencies.

Individual Frequencies

10 Hz: The regression analysis indicated that the two predictors accounted for 29% of the variance. The slope was significantly different from zero [$F(1,16) = 6.49$, $p = 0.022$]. There was a significant correlation between the eyes-closed alpha power at 10 Hz and the VSAT percentile score ($r = 0.54$, $p = 0.022$).

Alpha Attenuation Ratio: Correlation with VSAT

Linear regression analysis was used to compare the alpha attenuation ratio from the eyes-closed to the eyes-open condition ($AAR_{2:1}$) at each frequency to the respective VSAT percentile score for each subject. Results for each significant frequency and/or frequency band are given below.

Individual Frequencies

8 Hz: The regression analysis indicated that the two predictors (i.e., alpha attenuation ratio and VSAT score) explained 31% of the variance. The slope was significantly different from

zero [$F(1,16) = 7.128, p = 0.017$]. There was a significant correlation between the attenuation ratio at 8 Hz and the VSAT percentile score ($r = 0.55, p = 0.017$).

9 Hz: The regression analysis indicated that the two predictors accounted for 42% of the variance. The slope was significantly different from zero [$F(1,16) = 11.55, p = 0.004$]. There was a significant correlation between the attenuation ratio at 9 Hz and the VSAT percentile score ($r = 0.65, p = 0.004$).

10 Hz: The regression analysis indicated that the two predictors accounted for 48% of the variance; this was the highest r^2 value among the individual frequencies (Figure 3). The slope was significantly different from zero [$F(1,16) = 14.62, p = 0.002$]. There was a significant correlation between the attenuation ratio at 10 Hz and the VSAT percentile score ($r = 0.69, p = 0.002$).

Combined Frequency Bands

Lower (8–10 Hz): The regression analysis indicated the two predictors accounted for 46% of the variance; this was the highest r^2 value among the frequency bands. The slope was significantly different from zero [$F(1,16) = 13.43, p = 0.002$]. There was a significant correlation between the average attenuation ratio from 8–10 Hz and the VSAT percentile score ($r = 0.68, p = 0.002$). See Figure 4.

All (8–13 Hz): The regression analysis indicated the two predictors accounted for 28% of the variance. The slope was significantly different from zero [$F(1,16) = 6.20, p = 0.024$]. There was a significant correlation between the average attenuation ratio from 8–13 Hz and the VSAT percentile score ($r = 0.53, p = 0.024$).

Repeatability and Variability

Repeatability measures of both the VEP and alpha components were performed. We assumed that if the CV were relatively low, for data summed across the two sessions, that this would be an indicator of good repeatability. To assess repeatability of the VEP measurements, the CV was calculated for the N75 latency, P100 latency, and VEP amplitude using data obtained over the 2 sessions with three trials per condition. The CV ranged from 0.01 to 0.04 for the N75 latency, from 0.01 to 0.04 for the P100 latency, and from 0.04 to 0.24 for the VEP amplitude. To assess repeatability of the alpha wave measurements, the CV was also calculated using data over the two sessions with three trials per condition. The CV ranged from 0.42 to 0.76 at 8 Hz, 0.47 to 0.76 at 9 Hz, 0.45 to 0.68 at 10 Hz, 0.33 to 0.74 at 11 Hz, 0.36 to 0.72 at 12 Hz, and 0.43 to 0.66 at 13 Hz. Across all frequencies and subjects, the mean CV ranged from 0.48 to 0.64 for the alpha wave. See Table 4.

Discussion

There are several aspects that make the results of the present study unique. (1) This is the first study to quantify the difference in alpha power between the “eyes-open” and the “eyes-closed resting” conditions in the primary visual cortex in normals. Fuller [25] had only

investigated differential “eyes-closed” conditions in normals. (2) This is the first study to correlate the objectively assessed individual alpha values to a commonly-used subjective test of visual attention (VSAT). (3) In addition to the above correlation, differences in mean alpha power, variability, and repeatability among the six individual alpha band frequencies were quantitatively assessed, compared, and reported in detail here, which has never been done to date.

Alpha Attenuation

The results of the present study allow, for the first time, the ability to obtain an objective indicator of human visual attention that can be used both in the laboratory and clinical environments incorporating attentional differences in eyes-open and eyes-closed test conditions. The present findings demonstrated that the alpha power in the eyes-closed condition was, on average, approximately twice as large as that found with the eyes-open condition. An $AAR_{2;1}$ of >1.0 reflected some degree of alpha damping ability, while an $AAR_{2;1}$ of 2.0 was deemed to reflect considerably greater attenuation ability (i.e., two-fold), as the mean attenuation across all frequencies was 1.96. Furthermore, at the critical 10 Hz frequency, the mean attenuation value was 2.17. Across all subjects and frequencies measured, attenuation of the alpha wave to some degree from the eyes-closed to the eyes-open condition was present 83% of the time. This power difference between the eyes-closed and the eyes-open conditions was significantly different at five out of the six frequencies measured: the exception was the 8 Hz component. At 9, 10, and 11 Hz, which had the largest mean alpha attenuation ratios (1.85, 2.17, 2.93, respectively), attenuation was observed in 94%, 89%, and 94% of the sample, respectively.

With respect to the present alpha band data and related variability, it is important to determine when a difference in attenuation ratio is considered to be “significantly” different. The normative data from the present study can be used to examine this issue. For example, at 10 Hz, the mean was approximately 2.2, with an SEM of approximately 0.25. Thus, the mean $\pm$ 1 SEM ranged from 1.95 to 2.45 (Table 3). Thus, if one were to consider a difference in $AAR_{2;1}$ ratios significant at 10 Hz, the difference between the two mean values should exceed this range of 0.5. Similarly, this information could be used to assess repeatability, wherein now the difference should *not* exceed the specified range. The high frequency and large magnitude of attenuation at these frequencies, along with their low variability, suggest that attenuation of this alpha wave sub-band during visual processing is a predictable and repeatable measure. This finding is consistent with studies spanning the past seventy-five years [14,15,16], and thus confirms and extends a common observation.

Furthermore, the findings are corroborated with a well-known, standardized clinical test of visual attention, namely the VSAT. 83% of the present sample scored within the normal range on the VSAT, with the other 17% scoring above the abnormal range in a score band deemed “borderline” by its developers. This distribution of scores in the present sample suggests a large spectrum of visual attentional capability among visually-normal individuals. There was also a large range of alpha attenuation ratios, thus allowing for a possible correlation with the VSAT scores; in fact, correlations were significant at 8, 9, and 10 Hz. The significant correlation between the ratio of eyes-closed to eyes-open alpha power at

these lower-band frequencies provides a non-invasive, and objective, electrophysiological link to the process of visual attention. The present findings suggest that individuals with high alpha attenuation ratios are predicted to have superior visual attention skills when compared to individuals with lower ratios. This strongly supports the early pioneering findings and concepts of Grey Walter [22] and Ludlam [11,12], of whom both speculated that the inability to attenuate alpha may be related to reading and learning problems, in conjunction with an underlying and concurrent attentional deficit. In the present study, subjects who had attenuation ratios closest to one scored poorest on the VSAT and vice versa. These subjects who scored lowest can still be considered part of the normal population, but may simply have less visual-attentional ability than those who scored much higher.

The 10 Hz alpha component appears to be the key alpha band component: it had the largest power across all conditions; was close to the peak frequency for all subjects; had the second highest mean attenuation ratio from the eyes-closed to the eyes-open condition; exhibited the highest mean attenuation from the eyes-closed to the eyes-closed number counting condition; and, lastly, demonstrated the strongest correlation with the VSAT scores. Additionally, the coefficient of variability indicated that the 10 Hz component was the second-least variable frequency across conditions. Thus, it appears that this component of the alpha power spectrum is a prime candidate for clinical use: it combines a strong and repeatable objective measurement with a large range of subjective attentional scores for possible correlation.

The alpha wave power between the eyes-closed number counting and the eyes-closed condition ($AAR_{3;2}$) was not significantly different, but some degree of attenuation was found sixty-three percent of the time across all frequencies, most often at 10 Hz (eighty-three percent of the sample). The eyes-closed number counting to eyes-closed comparison in the current study yielded remarkably similar results to that of Fuller [25]. Across all frequencies, he found an average ratio of 0.93, whereas in the current study an $AAR_{3;2}$ of 0.95 was found. Although the magnitude of attenuation between these two conditions was not large, it occurred more than half the time, and thus suggested that there was some effect of attention on the eyes-closed alpha rhythm. Therefore, using the eyes-closed number counting to eyes-closed comparison may still be useful for differentiating certain clinical populations (e.g., ADHD, mTBI) from normals. This should be explored in the future.

Alpha: RSVP Tasks

The lack of significant differences between any of the three RSVP conditions supports Legewie's [17] finding that the differential effect of attention on the already attenuated eyes-open alpha is by necessity small, which likely represents a saturation (i.e., floor) effect. This is supported by previous literature: large band power in the reference interval is associated with a large amount of desynchronization during task performance [36]. Therefore, if the alpha power is already small (i.e., desynchronized) after opening the eyes, there is little possibility for much further attenuation. The large band power during the reference interval (i.e., eyes closed) was not significantly correlated with VSAT scores, except at 10 Hz. However, at 10 Hz, absolute power during the eyes-closed condition explained less of the

variance in VSAT performance than did the attenuation ratio. This eliminates the possibility that the amount of attenuation could be predicted by the absolute power of the alpha band alone.

Dynamic, attentionally-related changes in alpha must also occur outside of the laboratory under naturalistic viewing conditions. In the present experiment, subjects were purposely placed in a chair with a head/chinrest and requested to remain still, so that any head, eye, and/or body movement was minimized and would not create artifacts in the data. However, in a real-life situation, there would likely be frequent, transient changes in our attentional state [6] as one walks, gazes about, and attempts to grasp an object of interest. Measuring these sensitive, transient, and dynamic attentional shifts/effects would likely be difficult to achieve in the above scenario due to the creation of undesirable artifacts/noise in the recordings/etc. Additionally, mirroring transient shifts in attention, the attentionally-related desynchronization of alpha is hypothesized to function as a quick (on the order of ms) thalamocortical attentional gating mechanism: summation over large amounts of time would need to be performed before a desirable magnitude of this phenomenon could be recorded.

Moreover, the results of the present experiment related to conditions 4–6 indicate that the alpha wave did not change significantly with presumed variation in attentional demand with the eyes open. This again is likely due to a floor/saturation effect. However, it might be possible to assess this effect in a seated individual with eyes fixed in primary position, but with attention shifting periodically between the fixation target and an object in the near retinal periphery.

Alpha Wave Sub-bands

The significant correlations among the lower frequencies (8, 9, and 10 Hz) with the VSAT scores, in combination with the lack of significant correlations among the upper frequencies (11, 12, and 13 Hz) and the VSAT scores, strongly support Klimesch's [6] description of lower alpha sub-bands that desynchronize with attention. The VSAT is a task of visual attention requiring the subject to execute rapid and numerous visual discriminations, and furthermore execute frequent saccades to shift their eyes and visual attention across the page at a quick pace. Thus, an attentionally-derived, lower-alpha desynchronization would in fact be expected during the task. When taken as a group, the attenuation ratio of the 8–10 Hz band significantly correlated to the VSAT score, which suggests that it may also be useful to look at other alpha sub-bands (e.g., the lower $[f_p - 4]$ to $[f_p]$ band or the upper $[f_p]$ to $[f_p + 2]$ band) in addition to the individual frequencies. However, the present findings suggest that it may not be optimal to measure and incorporate all component frequencies within the 8–13 Hz range as a global and objective attentional parameter.

Clinical and Physiological Implications

The present results show a range of visual attention abilities in the normal population, and an even wider one may exist among special clinical populations, such as those with ADHD. The current diagnostic criteria to assess ADHD are broad and suggest that a heterogeneous population of children exist with this diagnosis [37]. The alpha attenuation ratio comparing the eyes-closed to eyes-open condition appears to serve as a good indicator as to the amount

of visual processing occurring, and thus may be predictive of visual attentional dysfunction in undiagnosed infants and children. It may be an effective screening procedure in these populations to detect those individuals that may be “at risk”, and thus be carefully followed over the subsequent early years of life. Other clinical populations for study may include individuals with TBI, in whom the attenuation ratio could be compared with other cognitive clinical tests of attention (e.g., Conners’ CPT [38]), and stroke patients with visual neglect, in whom the attenuation ratios of the two hemifields could be compared with traditional clinical tests of visual neglect (e.g., line bisection; [39]). Many ADHD-related electroencephalographic studies have assessed this global brain profile across the entire scalp [40,41], whereas the current study only assessed activity from the primary visual cortex (V1). The present results demonstrate that visual attention may be modulated as early as V1, in agreement with earlier studies [42,43,44].

The aforementioned studies [42,43,44] have revealed functional, pharmacological, and electrophysiological mechanisms of attentional modulation in V1. Using fMRI scans, Somers et al. [42] demonstrated strong attentional modulation in the primary visual cortex, while subjects fixated and attended to foveal and non-foveal stimuli, thus revealing that V1 exhibited similar characteristics to those found in the extrastriate cortices. This modulation was later shown to be enhanced by low doses of acetylcholine at muscarinic receptors and reduced by muscarinic antagonists in macaque monkeys [43], thus delineating a cellular pathway to enhance attention in the primary visual cortex. On a larger scale, Bollimunta et al. [44] have identified alpha current generators in layers of V1 (e.g., V1 layer 4C and V1 layer 6) and linked their activity to thalamocortical circuits, thus suggesting a possible neuroanatomical origin of alpha and also supporting earlier studies [45,46].

The temporal associations of attentional modulation via alpha wave desynchronization in the primary visual cortex have been well described in the literature. Several studies have suggested that lateralized, event-related desynchronization (i.e., ERD, measured hundreds of milliseconds before the stimulus presentation) of posterior lobe alpha activity places the brain in a “ready” mode in which visual information can be more readily detected, extracted, and processed from the external environment, thus preparing the subject to respond to both real and potential stimuli. Thus, alpha ERD may be related to the formation and maintenance of an attentional template [47], as well as improved behavioral detection and/or discriminatory performance [48,49]. Conversely, Hanslmayer [50] has shown that those with synchronous (i.e., high power) alpha activity in parieto-occipital regions during pre-stimulus periods performed poorly on a visual discrimination task. The current study supports the relationship between desynchronization and enhanced visual-spatial attention ability, but over a much larger time scale (e.g., one minute VSAT test time and 20 second VEP alpha trials). Whereas ERD’s are measured over milliseconds, the current study’s protocols are more akin to Ludlam’s [11,12] and Fuller’s [25] measures. Thus, clinical measurement of the occipital alpha-attenuation ratio may serve as a less dexterous, yet equally as effective, method to capture and describe the dynamic attentional processes of the brain.

Quality of Data

All subjects exhibited low variability with respect to their VEP amplitudes, therefore suggesting that they were fixating well at all times, since the pattern-reversal VEP is sensitive to fixational instabilities and saccadic eye movements [1]. Subjects also exhibited low variability across all latency measurements. It can then be assumed that each subject had optimal vision, and, furthermore that the data were not affected by any optical/refractive source of error. The very low coefficient of variability values for the VEP parameters, similar to those found by Tello et al. [51], suggest that it is a repeatable measure if performed on two separate days with at least three trials per condition.

Electroencephalographic signals show a large amount of variability across time [35], therefore necessitating the need for precise measures and adequate recording time. In the present sample, alpha CV values ascertained with 20 second “eyes closed” and “eyes open” trials (0.48–0.64) had a similar range to those found previously (0.58–0.76) by Maltez et al. [35], who selected 4 second epochs of eyes closed alpha. The aforementioned study also found that use of a 20 second test duration was sufficient for determination of the alpha peak frequency.

In addition to optimal quality of vision, measurement of the correct alpha bandwidth is important to consider. All subjects had a peak frequency close to 10 Hz ($\bar{X} = 10.33$ Hz, SEM= 0.03), thus eliminating any chance that portions of a subject’s alpha bandwidth fell outside of the range measured. Thus, all possible alpha-wave frequencies for each subject were measured and analyzed.

Study Limitations

There were four possible limitations to the present study. First, a digital read-out would improve precision of the numerical values from the power spectrum plots; current resolution is approximately $1 \mu\text{v}^2$. Second, there was a likely saturation effect regarding the power spectrum scale: the maximum graphical value was $60 \mu\text{v}^2$, so that any power value greater than 60 would not be accurately depicted. This was done initially for graphical scaling purposes related to conventional VEP measures and related power spectrum. Since the largest amplitude values for the alpha power spectrum were at the mid-range frequencies of 10 to 11 Hz, the present findings thus represent a conservative estimate of alpha attenuation. With greater scale values, the results would likely be even more robust; however, this effect is likely to be small as the power equalled or exceeded $60 \mu\text{v}^2$ in only 1.5% of the trials. Thirdly, stimuli of different contrast (e.g., low) and luminance (e.g., low) were not included. However, given the relatively small alpha band signals using the present high contrast and luminance levels, such less effective stimuli may not have elicited reliable and/or adequate response magnitudes. Fourth, and lastly, the present study had a narrow age range. This was done purposefully to avoid age-related contamination effects [19]. As mentioned previously, the alpha peak frequency decreases with age, at a rate of approximately 0.046 Hz/yr after age 20 [19]. Such an expected age-related change would likely have to be compensated in one’s laboratory/clinical test results, for example by shifting the alpha bandwidth used for assessment to bias this lower peak frequency. To provide generality across the age-spectrum, additional studies need to be performed, which compensate for the new peak frequency and bandwidth.

Future Directions

There are possible future research directions based on the findings of the present study. First, the goal for the immediate future is to perform the present test protocol on specific clinical populations (e.g., TBI) known to exhibit attentional deficits [39]. Mild traumatic brain injured (mTBI) patients have been shown to have attenuated posterior-lobe alpha power within hours following, and then permanently, after the injury [52]. The amount of EEG abnormality has been shown to vary with severity of the mTBI; such deficits present twenty-four hours post-injury can be predictive of a poor prognosis [52]. Second, since peak alpha frequency changes with age, subjects of different age groups should be tested to determine whether or not 10 Hz alpha (the peak frequency of subjects in our sample) still correlates strongly with VSAT scores of other age groups, or if the peak frequency among the different age groups maintains the strongest correlation. Other interests for the future include simplifying the test protocol (e.g., performing conditions 1 and 2 only), performing another subjective test of visual attention (e.g., anti-saccade test [53]) to investigate additional possible correlation with the alpha attenuation ratio, and lastly, to compare occipital findings with other areas of the brain (e.g., frontal and parietal lobes [54]).

Conclusions

The alpha wave provides an objective, electrophysiological measure of visual attention. Furthermore, it was found to be correlated with a standard subjective clinical test of visual attention. Lastly, the present findings suggest that human visual attention may be detected, assessed, and modulated as early as the primary visual cortex.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

We would like to thank the National Institutes of Health (NIH) 5T35EY02048103 fellowship program for their generous support, along with Diopsys™ Inc for use of their equipment.

References

1. Odom JV, Bach M, Brigell M, Holder GE, McCulloch DL, Tormene AP, Vaegan. ISCEV standard for clinical visual-evoked potentials (2009 update). *Doc Ophthalmol.* 2009; 120:111–119. [PubMed: 19826847]
2. Yadav NK, Almqvist F, Head L, Irving EL, Leat SJ. Threshold determination in sweep VEP and the effects of criterion. *Doc Ophthalmol.* 2009; 119:109–121. [PubMed: 19554357]
3. Almqvist FM, Yadav NK, Leat SJ, Head LM, Irving EL. Effects of sweep VEP parameters on visual acuity and contrast thresholds in children and adults. *Graefes Arch Clin Exp Ophthalmol.* 2011; 249:613–623. [PubMed: 20694474]
4. Politzer, T.; Suter, PS. Vision examination of patients with neurological disease and injury. In: Suter, PS.; Harvey, LH., editors. *Vision rehabilitation: multidisciplinary care of the patient following brain injury.* Taylor and Francis Group; Boca Raton: 2011. p. 427-460.
5. Berger H. Ueber des elektrenkephelogramm des menschen. *Arch Psychiat Nervenkr.* 1929; 87:527–570.

6. Klimesch W. EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. *Brain Res.* 1999; 29:169–195.
7. Feige B, Scheffler K, Esposito F, Di Salle F, Jurgen H, Seifritz E. Cortical and subcortical correlates of electroencephalographic alpha rhythm modulation. *J Neurophysiol.* 2005; 93:2864–2872. [PubMed: 15601739]
8. Gomarús HK, Wijers AA, Minderaa RB, Althaus M. Do children with ADHD and/or PDD-NOS differ in reactivity of alpha/theta ERD/ERS to manipulations of cognitive load and stimulus relevance? *Clin Neurophysiol.* 2009; 120:73–79. [PubMed: 19059001]
9. Luria, AR. Higher cortical functions in man. Basic Books; New York: 1966.
10. Niedermeyer, E.; Lopes da Silva, F., editors. *Electroencephalography: basic principles, clinical applications, and related fields.* 3. Williams and Wilkins; Baltimore: 1993.
11. Ludlam, WM. Review of psycho-physiological factors in visual information processing as they relate to learning. In: Greenstein, T., editor. *Vision and learning disability.* J Am Optom Assoc; St Louis: 1976. p. 179-222.
12. Ludlam WM. Visual training, the alpha activation cycle, and reading. *J Am Optom Assoc.* 1979; 50:111–115. [PubMed: 762372]
13. Babiloni F, Cincotti F, Babiloni C, Carducci F, Mattia D, Astolfi L, Basilisco A, Rossini PM, Ding L, Ni Y, Cheng J, Christine K, Sweeney J, He B. Estimation of the cortical functional connectivity with the multimodal integration of high-resolution EEG and fMRI data by directed transfer function. *Neuroimage.* 2005; 24:118–131. [PubMed: 15588603]
14. Adrian ED, Matthews BHC. The berger rhythm: potential changes from the occipital lobes in man. *Brain.* 1934; 57:355–385.
15. Gale A, Coles M, Boyd E. Variation in visual input and the occipital EEG. *Psychonomic Science.* 1971; 23:99–100.
16. Mann CA, Serman MB, Kaiser DA. Suppression of EEG rhythmic frequencies during somato-motor and visuo-motor behavior. *Int J Psychophysiol.* 1996; 23:1–7. [PubMed: 8880361]
17. Legewie H, Simonova O, Creutzfeldt OD. EEG changes during performance of various tasks under open and closed-eyed conditions. *Electroencephalogr Clin Neurophysiol.* 1969; 27:470–479. [PubMed: 4187033]
18. Gotman J, Wang LY. State-dependent spike detection: concepts and preliminary results. *Electroencephalogr Clin Neurophysiol.* 1991; 79:11–19. [PubMed: 1713547]
19. Kopruner, V.; Pfurtscheller, G.; Auer, LM. Quantitative EEG in normals and in patients with cerebral ischemia. In: Pfurtscheller, G.; Jonkman, EJ.; Lopes da Silva, FH., editors. *Brain ischemia: quantitative EEG and imaging techniques, progress in brain research.* Vol. 62. 1984. p. 29-50.
20. Helvie, R. Neural substrates of vision. In: Suter, PS.; Harvey, LH., editors. *Vision rehabilitation: multidisciplinary care of the patient following brain injury.* Taylor and Francis Group; Boca Raton: 2011. p. 45-76.
21. American Clinical Neurophysiology Society. Guideline 5: guidelines for standard electrode position nomenclature. *J Clin Neurophysiol.* 2006; 23:107–110. [PubMed: 16612226]
22. Walter, WG. *The Living Brain.* WW Norton and Co Inc; New York: 1963.
23. Ciuffreda KJ. The scientific basis for and efficacy of optometric vision therapy in nonstrabismic accommodative and vergence disorders. *Optometry.* 2002; 73:735–762. [PubMed: 12498561]
24. Solan HA, Shelley-Tremblay J, Ficarra A, Silverman M, Larson S. Effect of attention therapy on reading comprehension. *J Learn Disabil.* 2003; 36:556–563. [PubMed: 15493437]
25. Fuller P. Attention and the EEG alpha rhythm in learning disabled children. *J Learn Disabil.* 1978; 11:303–312. [PubMed: 670819]
26. Yadav NK, Ludlam DP, Ciuffreda KJ. Effect of different stimulus configurations on the visual evoked potential (VEP). *Doc Ophthalmol.* 2012; 124:177–196. [PubMed: 22426575]
27. Ciuffreda KJ, Yadav NK, Ludlam DP. Effect of binasal occlusion (BNO) on the visual-evoked potential (VEP) in mild traumatic brain injury (mTBI). *Brain Inj.* 2012 in press.
28. Trenerry MR, Crosson B, DeBoe J, Leber WR. Professional manual: visual search and attention test. Psychological Assessment Resources, Lutz. 1989

29. Benjamin, WJ. Borish's Clinical Refraction. 2. Butterworth-Heinemann; St. Louis: 2006.
30. Smith A. The serial sevens subtraction test. *Arch Neurol*. 1967; 17:78. [PubMed: 6026175]
31. Bradley JV. Complete counterbalancing of immediate sequential effects in a latin square design. *J Amer Statist Assoc*. 1958; 53:525–528.
32. Squires N, Squires K, Hillyard S. Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli in man. *Electroencephalogr Clin Neurophysiol*. 1975; 38:387–401. [PubMed: 46819]
33. Dumermuth G. Spectral analysis of the EEG. *Neuropsychobiology*. 1987; 17:85–99. [PubMed: 3306442]
34. Salkind, N., editor. *Encyclopedia of research design*. Sage; Thousand Oaks: 2010.
35. Maltez J, Hyllienmark L, Nikulin VV, Brismar T. Time course and variability of power in different frequency bands of EEG during resting conditions. *Clin Neurophysiol*. 2004; 34:195–202.
36. Chiappa, KH. *Evoked potentials in clinical medicine*. Raven Press; New York: 1990.
37. Doppelmayr M, Klimesch W, Pachinger T, Ripper B. The functional significance of absolute power with respect to event-related desynchronization. *Brain Topogr*. 1998; 11:133–140. [PubMed: 9880171]
37. Mann CA, Lubar JF, Zimmerman AW, Miller CA, Muenchen RA. Quantitative analysis of EEG in boys with attention-deficit-hyperactivity disorder: controlled study with clinical implications. *Pediatr Neurol*. 1992; 8:30–36. [PubMed: 1558573]
38. Conners, KC. *Conners' Continuous Performance Test II [Manual]*. Multi-Health Systems Inc; Toronto: 2004.
39. Suchoff, IB.; Ciuffreda, KJ.; Kapoor, N., editors. *Optometric Extension Program*. Santa Ana; 2001. Visual and vestibular consequences of acquired brain injury.
40. Chabot R, Serfontein G. Quantitative electroencephalographic profiles of children with attention deficit disorder. *Biol Psychiatry*. 1996; 40:951–963. [PubMed: 8915554]
41. Clarke AR, Barry RJ, McCarthy R, Selikowitz M. EEG analysis in attention- deficit/hyperactivity disorder: a comparative study of two subtypes. *Psychiatry Res*. 1998; 81:19–29. [PubMed: 9829647]
42. Somers DC, Dale AM, Seiffert AE, Tootell RBH. Functional MRI reveals spatially specific attentional modulation in human primary visual cortex. *Proc Natl Acad Sci USA*. 1999; 96:1663–1668. [PubMed: 9990081]
43. Herrero JL, Roberts MJ, Delicato LS, Gieselmann MA, Dayan P, Thiele A. Acetylcholine contributes through muscarinic receptors to attentional modulation in V1. *Nature*. 2008; 454:1110–1114. [PubMed: 18633352]
44. Bollimunta A, Mo J, Schroeder CE, Ding M. Neuronal mechanisms and attentional modulation of corticothalamic alpha oscillations. *J Neurosci*. 2011; 31:4935–4943. [PubMed: 21451032]
45. Lopes da Silva FH, Vos JE, Mooibroek J, Van Rotterdam A. Relative contributions of intracortical and thalamocortical processes in the generation of alpha rhythms, revealed by partial coherence analysis. *Electroencephalogr Clin Neurophysiol*. 1980; 50:449–456. [PubMed: 6160987]
46. Hughes SW, Crunelli V. Just a phase they're going through: the complex interaction of intrinsic high-threshold bursting and gap junctions in the generation of thalamic alpha and theta rhythms. *Int J Psychophysiol*. 2007; 64:3–17. [PubMed: 17000018]
47. Tineke G, Boehler CN, Kenemans JL, Woldorff MG. Differential functional roles of slow-wave and oscillatory alpha activity in visual sensory cortex during anticipatory visual-spatial attention. *Cereb Cortex*. 2011; 21:2204–2216. [PubMed: 21372123]
48. Kelly SP, Gomez-Ramirez M, Foxe JJ. The strength of anticipatory spatial biasing predicts target discrimination at attended locations: a high-density EEG study. *Eur J Neurosci*. 2009; 30:2224–2234. [PubMed: 19930401]
49. van Dijk H, Schoffelen JM, Oostenveld R, Jensen O. Prestimulus oscillatory activity in the alpha band predicts visual discrimination ability. *J Neurosci*. 2008; 28:1816–1823. [PubMed: 18287498]
50. Hanslmayr S, Aslan A, Staudigl T, Klimesch W, Hermann CS, Bäuml CH. Prestimulus oscillations predict visual perception performance between and within subjects. *Neuroimage*. 2007; 37:1465–1473. [PubMed: 17706433]

51. Tello C, De Moraes CGV, Prata TS, Derr P, Patel J, Siegfried J, Liebmann JM, Ritch R. Repeatability of short-duration transient visual evoked potentials in normal subjects. *Doc Ophthalmol.* 2010; 120:219–228. [PubMed: 20111979]
52. Arciniegas DB. Clinical electrophysiological assessments and mild traumatic brain injury: state-of-the-science and implications for clinical practice. *Int J Psychophysiol.* 2011; 82:41–52. [PubMed: 21419178]
53. Ciuffreda, KJ.; Tannen, B. Eye movement basics for the clinician. Mosby-Year Book Inc; St. Louis: 1995.
54. Corbetta M, Shulman GL. Control of goal-directed and stimulus-driven attention in the brain. *Nat Rev Neurosci.* 2002; 3:201–215. [PubMed: 11994752]

Fig. 1a

Fig. 1b

Fig. 1.

Fig. 1a. The Diopsys™ NOVA-TR System for VEP testing (A) The experimenter's display monitor (B) Stimulus monitor

Fig. 1b. The experimental apparatus for RSVP testing (A) RSVP Test Monitor (B) The experimenter's display monitor (C) Headrest/chinrest

Fig. 2.

Average alpha power values across the six test conditions, at each frequency ($\bar{X} \pm 1$ SEM)

Fig. 3.
Correlation between the attenuation ratio at 10 Hz and the VSAT percentile score

Fig. 4.
Correlation between the attenuation ratio in the lower alpha band (8–10 Hz) and the VSAT percentile score

Table 1
Post-Hoc Analyses For Group Mean Power Spectrum Data For The Six Test Conditions

8 Hz	1	2	3	4	5	6	9 Hz	1	2	3	4	5	6
1							1		*	*			
2					*		2				*	*	*
3							3					*	
10 Hz	1	2	3	4	5	6	11 Hz	1	2	3	4	5	6
1		*	*				1		*	*			
2				*	*	*	2				*	*	*
3				*	*	*	3				*	*	*
12 Hz	1	2	3	4	5	6	13 Hz	1	2	3	4	5	6
1		*					1		*				
2				*	*	*	2				*	*	*
3						*	3						

* Indicates a significant difference ($p < 0.05$)

Table 2

Group Mean Alpha Attenuation Ratios For Each Frequency

	AAR _{2:1}	AAR _{3:2}	AAR _{2:1}	AAR _{3:2}	AAR _{2:1}	AAR _{3:2}
	8 Hz		9 Hz		10 Hz	
RANGE [Min-Max]	0.56–5.68	0.42–1.70	0.95–4.40	0.44–1.51	0.86–4.88	0.38–1.51
MEAN	1.51	0.98	1.85	0.95	2.17	0.87
SD	1.19	0.33	0.83	0.32	1.10	0.29
SEM	0.28	0.08	0.19	0.07	0.26	0.07

	AAR _{2:1}	AAR _{3:2}	AAR _{2:1}	AAR _{3:2}	AAR _{2:1}	AAR _{3:2}
	11 Hz		12 Hz		13 Hz	
RANGE [Min-Max]	0.98–14.94	0.67–1.57	0.31–3.93	0.43–2.32	0.62–3.83	0.36–1.49
MEAN	2.93	1.07	1.57	0.99	1.78	0.87
SD	3.16	0.26	0.88	0.46	0.88	0.28
SEM	0.75	0.06	0.21	0.11	0.21	0.06

Table 3

Group Mean and Individual Subject Data: Alpha Attenuation Ratio and Coefficient of Variation (CV)

	8 Hz	9 Hz	10 Hz	11 Hz	12 Hz	13 Hz	MEAN
S1	0.79	1.85	1.57	4.43	1.62	1.82	<u>2.01</u>
S2	1.49	1.83	3.39	2.60	1.77	3.03	<u>2.35</u>
S3	1.05	2.23	1.98	2.49	0.92	1.08	<u>1.63</u>
S4	1.36	1.73	3.02	3.08	2.67	2.45	<u>2.39</u>
S5	0.87	0.95	1.59	1.27	2.56	2.61	<u>1.64</u>
S6	0.63	1.00	0.86	1.02	0.94	1.51	<u>0.99</u>
S7	0.73	1.08	1.56	0.98	0.31	0.62	<u>0.88</u>
S8	1.52	2.51	2.99	3.37	1.83	2.77	<u>2.50</u>
S9	0.56	1.20	1.10	3.56	1.47	2.15	<u>1.67</u>
S10	2.48	2.91	2.28	1.14	1.13	1.21	<u>1.86</u>
S11	1.55	2.15	4.04	1.54	1.20	1.86	<u>2.06</u>
S12	0.66	1.13	0.88	1.33	0.56	1.20	<u>0.96</u>
S13	0.99	1.57	1.30	3.25	2.24	1.77	<u>1.85</u>
S14	5.68	4.40	4.88	14.94	3.93	3.83	<u>6.28</u>
S15	1.23	1.67	1.54	1.70	1.22	1.13	<u>1.42</u>
S16	2.14	1.72	1.98	1.84	1.44	0.89	<u>1.67</u>
S17	2.33	1.61	2.00	2.60	1.73	1.00	<u>1.88</u>
S18	1.05	1.70	2.08	1.55	0.65	1.03	<u>1.34</u>
MEAN	<u>1.51</u>	<u>1.85</u>	<u>2.17</u>	<u>2.93</u>	<u>1.57</u>	<u>1.78</u>	
SD	<u>1.19</u>	<u>0.83</u>	<u>1.10</u>	<u>3.16</u>	<u>0.88</u>	<u>0.87</u>	
SEM	<u>0.29</u>	<u>0.32</u>	<u>0.35</u>	<u>0.40</u>	<u>0.29</u>	<u>0.31</u>	
CV	<u>0.79</u>	<u>0.45</u>	<u>0.51</u>	<u>1.08</u>	<u>0.56</u>	<u>0.49</u>	

Table 4
Group Mean and Individual Subject Data: Power Spectrum Coefficient of Variability (CV) At Each Frequency

	8 Hz	9 Hz	10 Hz	11 Hz	12 Hz	13 Hz	MEAN
S1	0.62	0.64	0.56	0.33	0.39	0.44	<u>0.48</u>
S2	0.52	0.61	0.54	0.65	0.45	0.54	<u>0.56</u>
S3	0.71	0.57	0.51	0.54	0.44	0.46	<u>0.55</u>
S4	0.57	0.47	0.58	0.52	0.72	0.58	<u>0.57</u>
S5	0.60	0.51	0.46	0.52	0.58	0.66	<u>0.55</u>
S6	0.56	0.60	0.65	0.52	0.39	0.63	<u>0.55</u>
S7	0.57	0.76	0.68	0.59	0.63	0.65	<u>0.64</u>
S8	0.46	0.50	0.61	0.50	0.44	0.59	<u>0.52</u>
S9	0.42	0.55	0.55	0.58	0.46	0.48	<u>0.51</u>
S10	0.47	0.57	0.54	0.62	0.70	0.58	<u>0.57</u>
S11	0.63	0.63	0.54	0.55	0.64	0.63	<u>0.60</u>
S12	0.76	0.61	0.48	0.61	0.56	0.43	<u>0.58</u>
S13	0.65	0.57	0.63	0.70	0.53	0.47	<u>0.60</u>
S14	0.69	0.60	0.45	0.43	0.48	0.52	<u>0.57</u>
S15	0.72	0.62	0.54	0.67	0.49	0.52	<u>0.59</u>
S16	0.47	0.59	0.49	0.49	0.36	0.53	<u>0.49</u>
S17	0.55	0.61	0.50	0.53	0.58	0.58	<u>0.56</u>
S18	0.57	0.66	0.45	0.74	0.56	0.55	<u>0.58</u>
MEAN	<u>0.59</u>	<u>0.59</u>	<u>0.54</u>	<u>0.56</u>	<u>0.52</u>	<u>0.55</u>	
SD	<u>0.10</u>	<u>0.07</u>	<u>0.07</u>	<u>0.10</u>	<u>0.11</u>	<u>0.07</u>	
SEM	<u>0.02</u>	<u>0.02</u>	<u>0.02</u>	<u>0.02</u>	<u>0.02</u>	<u>0.02</u>	