Objective assessment of visual attention in mild traumatic brain injury (mTBI) using visual-evoked potentials (VEP)

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Abstract

Purpose: To quantify visual attention objectively using the visual-evoked potential (VEP) in those having mild traumatic brain injury (mTBI) with and without a self-reported attentional deficit.

Research design and methods: Subjects were comprised of 16 adults with mTBI: 11 with an attentional deficit and five without. Three test conditions were used to assess the visual attentional state to quantify objectively the VEP alpha band attenuation ratio (AR) related to attention: (1) pattern VEP; (2) eyes-closed; and (3) eyes-closed number counting. The AR was calculated for both the individual and combined alpha frequencies (8–13 Hz). The objective results were compared to two subjective tests of visual and general attention (i.e. the VSAT and ASRS, respectively).

Results: The AR for both the individual and combined alpha frequencies was found to be abnormal in those with mTBI having an attentional deficit. In contrast, the AR was normal in those with mTBI but without an attentional deficit. The AR correlated with the ASRS, but not with the VSAT, test scores.

Conclusions: The objective and subjective tests were able to differentiate between those having mTBI with and without an attentional deficit. The proposed VEP protocol can be used in the clinic to detect and assess objectively and reliably a visual attentional deficit in the mTBI population.

Keywords

Alpha band power, attenuation ratio (AR), attention deficit, mild traumatic brain injury (mTBI), primary visual cortex (V1), visual attention, visual-evoked potential (VEP)

Introduction

Traumatic brain injury (TBI) is a major medical and public health concern in the US [1, 2]. Approximately 1.7 million people suffer from a TBI annually. The prevalence of TBI has increased in recent years due to the past Iraq/Afghanistan military encounters [3], as well as the greater appreciation of sports-related concussions [4] and possibly related neurodegenerative disorders (e.g. Alzheimer’s, Parkinson’s) [5]. Since 70–80% of TBI is of the ‘mild’ variety (i.e. mTBI), most research has focused in that direction [6, 7].

Mild traumatic brain injury (mTBI) occurs as a result of injury to the brain due to blunt or penetrating head trauma [8]. It produces widespread damage to the brain tissues due to the initial and immediate biomechanical effects (e.g. coup-contrecoup, shearing, etc.) [9], as well as the subsequent biomolecular/biochemical changes [10]. It causes diffuse axonal injury (DAI), which is responsible for slowed and delayed cortical information processing [11].

Due to its global nature, mTBI results in a constellation of adverse effects of a sensory, motor, perceptual, linguistic, cognitive and/or behavioural nature [12–14]. Since the majority of cranial nerves (i.e. II, III, IV, V, VI, VII and VIII) are involved in vision, as well as at least 30–40 distinct cortical areas of the brain [15], it is not surprising that visual deficits frequently occur following mTBI (e.g. oculomotor problems, visual-field defects, photosensitivity and increased visual motion sensitivity) [12, 16–19].

One of the most common visual sequelae of mTBI is a visual/general attentional deficit [14, 20–22]. Visual attention refers to use of the visual sense to perceive and process the incoming information, whereas general attention refers to the use of other senses as well, such as audition and taction, to perceive and process the incoming information, in both cases with excellent accuracy and without an abnormal delay. Individuals with mTBI having attentional deficits typically report problems reading, and they manifest slowed visual information processing, as well as general distractibility [17, 18, 20, 23]. Thus, the presence of an attentional deficit will likely have an adverse effect on many activities of daily living (ADLs), e.g. reading. Furthermore, it may have an adverse impact on the individual’s vocational and avocational goals, as well as rehabilitative progress [24].

There is a long, but sparse, history of using objective techniques to assess human attention. Berger [25] was the first to investigate the alpha band (8–13 Hz) electrophysiologically in the human brain. Decades later, Klimesch [26] found that the alpha band was related to human thalamo-cortical
attention. It has been confirmed that high levels of alpha power, which occur during the ‘relaxed’, eyes-closed attentional state, are associated with *synchronous* neuronal cortical activity. In contrast, low levels of alpha power, which occur during visual stimulation and visual-attentional engagement with the eyes-open, are associated with *asynchronous* neuronal cortical activity [26]. This comparison is presented in Figure 1. More recent studies have demonstrated that the level of alpha band activity was correlated with different attentional states: eyes-closed as compared to the eyes-open condition [27–29], eyes closed with increased attentional demand as compared to the eyes-closed condition [28, 30], visual imagery [31] and visual attention during reading [32]. These studies revealed that changes in neuronal activity occurred and were related to the different attentional states, thus producing predictable changes in the relative alpha band power contributions. Of particular importance is the following: attenuation of the alpha band amplitude occurs with the eyes-open as compared to the eyes-closed condition. This is a normal phenomenon: in fact, *inability to attenuate or suppress alpha during the eyes-open condition suggests presence of a visual attentional deficit* [28–30, 32, 33]. Thus, assessing the alpha band neuronal activity provides a non-invasive and direct route to probe the attentional state of an individual objectively. More recent studies performed by Kirschfeld [34] and Hale et al. [35], using the EEG technique, have also revealed that alpha band activity was related to one’s attentional state.

Most studies have concentrated on assessing attention in higher cortical areas, i.e. the parietal and temporal lobes [36–38]. However, some researchers have measured attention directly from the visual cortex (V1) to assess for its early visual pathway patency. For example, Fuller [30] investigated attention using the EEG method at a frequency band of 0.5–30 Hz in 10 children with learning disability (LD). Their responses were compared with 11 normal, age-matched children in two eyes-closed conditions. The alpha band was extracted from the overall EEG band, and then power spectrum analysis (described in the Methods section) was used to quantify the overall response and its sub-components. First, alpha power was recorded with the eyes-closed in a relaxed state for 5 minutes, so that any residual visually-based attentional aspects were allowed to dissipate. Then, a cognitive demand was added to the eyes-closed condition, that is the subjects performed simple addition, recall of common objects and a word problem task, all during which alpha brain wave activity was recorded. Fuller [30] calculated the alpha attenuation ratio (AR) between the average alpha power measured during the cognitively-demanding eyes-closed condition to the average alpha power measured during the eyes-closed ‘resting’ condition. An attenuation ratio of <1.00 suggested an ability to suppress alpha activity during the cognitively-demanding, eyes-closed condition, as expected to be the case for those with normal attention. Fuller found that 81% of the normal, age-matched children had an average attenuation ratio of 0.91. In comparison, 80% of the LD children had an average attenuation ratio of 1.01. Thus, children with LD were not able to suppress their alpha activity as well during the cognitively-demanding, eyes-closed condition, as compared to the normal children. Similar results were found by Ludlam [32].

Recently, Willeford et al. [28] used the above ideas and improved VEP hardware/software technology to assess normal human visual attention. They confirmed and extended Fuller’s earlier findings in 18 visually-normal, young-adults. The Willeford et al. [28] results obtained in the laboratory serve as the normative database for the present study. In the Willeford et al. [28] study, two different attenuation ratios (ARs) were calculated: the first was between the average alpha band power during the eyes-closed ‘relaxed’ attentional condition (EC) and the average alpha band power during the eyes-open condition (EO); and the second ratio was between

![Figure 1. Alpha attenuation for eyes-closed to eyes-open condition; x- and y-axis represent the alpha band frequency (Hz) and power magnitude (µV²), respectively.](image-url)
the average alpha band power during the eyes-closed number counting condition (ECNC) and the average alpha band power during the eyes-closed ‘relaxed’ attentional condition (EC). The EC ÷ EO AR was found to correlate with a standard subjective clinical visual attention test, namely the Visual Search and Attention Test (VSAT) [28, 39]. In addition, Willeford et al. [28] found the following: (1) alpha attenuation ratio (AR) (EC ÷ EO) values of 2 or greater, which suggested presence of normal visual attention; (2) the objectively-based AR at 10 Hz was significantly correlated with the subjectively-derived VSAT percentile score; and (3) the second alpha AR (ECNC ÷ EC) was less than 1, which was similar to Fuller’s [30] normative value. Lastly, the mean coefficient of variation (CV) values across all alpha wave frequencies and across all subjects ranged from 0.48–0.64, which was relatively small; this suggested good repeatability of the alpha wave responses. Thus, the Willeford et al. [28, 29] studies demonstrated that the VEP alpha wave component provided a reliable, objective correlate of human visual attention and, furthermore, significantly correlated with the subjective VSAT percentile score.

Lastly, Yadav et al. [40] quantitatively assessed the effect of oculumotor vision rehabilitation (OVR) [41] on the VEP responsivity and on visual attention in the mTBI population. Each individual (n = 7) received 9 hours of OVR over a period of 6 weeks. It included training of all three oculumotor systems (i.e. version, vergence, and accommodation), with an embedded visual attentional training element [42, 43]. Following successful OVR: VEP amplitude increased and its variability decreased; latency remained constant; the attentional AR (EC ÷ EO) increased at each alpha frequency and across frequencies; and the VSAT percentile score increased. These findings suggested that the OVR produced significant changes at the visuo-cortical level both with respect to vision and visual attention in this sample mTBI population. However, in this study, there was no attempt to use these objective and subjective techniques to detect and differentiate between those having mTBI with and without an attentional deficit.

Thus, the purpose of the present experiment was to quantify visual attention objectively using the visual-evoked potential (VEP) in those having mild traumatic brain injury (mTBI) with as compared to those without a self-reported visual attentional deficit. The hypothesis is that the VEP will be able to detect and assess objectively visual attentional deficits in the mTBI population. Those with mTBI and a visual attentional deficit are predicted to exhibit lack of neural, alpha-wave attenuation when comparing the EO and ECNC (i.e. increased attentional demand) conditions to the eyes-closed ‘relaxed’ attentional state (EC). In contrast, those without an attentional deficit are predicted to exhibit neural, alpha-wave attenuation.

**Methods**

**Subjects**

Sixteen individuals with medically-documented mTBI participated in this study: 11 with a self-reported visual/general attentional deficit (mean age = 38.0 years, SEM = 4.8 years) and five without (mean age = 29.8 years, SEM = 2.2 years). This attentional information was consistent with their clinical case history taken by a neuro-optometrist and a social worker in the college’s brain injury clinic, as well as with other supporting full medical and neuropsychological documentation. Brain injury resulted from either a motor vehicle accident (MVA), sports-related injury, fall or an assault, all occurring 4 months to 13 years (mean = 5.4 years) prior to the VEP testing. See Table I for subject demographics. The following criteria were used for the diagnosis of mTBI [44]: (1) loss of consciousness for less than 30 minutes or an altered state of consciousness for up to 24 hours, (2) 13 or greater score on the Glasgow Coma Scale (GCS) and (3) post-traumatic amnesia (PTA) lasting less than 24 hours. Most were referred to the Raymond J. Greenwald Rehabilitation Center (RJGRC)/Brain Injury Clinic at the SUNY, State College of Optometry, from rehabilitation professionals at the following institutions: Rusk Institute of Rehabilitative Medicine at NYU Medical Center, Bellevue Hospital at NYU Medical Center, Department of Rehabilitative Medicine at Mount Sinai Medical Center, Lenox Hill Hospital, New York Hospital and the International Center for the Disabled. In addition, some were referred from students and staff at the college. Each had corrected visual acuity of 20/20 or better in each eye at both distance and near. Exclusion criteria included a history of seizures, constant strabismus and amblyopia, as well as any type of ocular, systemic or neurological disease. The study was approved by the Institutional Review Board (IRB) at the SUNY, State College of Optometry. Written informed consent was obtained from all subjects.

**Apparatus**

The DIOPSYSTM NOVA-TR VEP system was used to assess both VEP responsivity (i.e. amplitude and latency) [19, 45, 46] and alpha band (8–13 Hz) power [28, 29, 40]. This system was used to generate an alternating checkerboard stimulus pattern, record the cortical responses and analyse the data. It has two monitors, one to present the test stimuli to the subject and a second for the experimenter to view the VEP and alpha responses online in real-time. In addition, artifact detection software was incorporated by the manufacturer to detect transients caused by blinks and/or saccadic eye movements. A custom-designed software program developed by the manufacturer was used to extract the alpha response information and process it quantitatively via power spectrum analysis [47]. Basically, with the power spectrum approach, at each frequency component of the response within the 8–13 Hz alpha wave signal embedded in the overall VEP frequency spectrum of 0.5–30 Hz, the signal magnitude is extracted and quantified (unit = μV2 = microvolt2 of the alpha band). The power at each frequency is plotted (see Figure 1). This is an excellent way to extract and quantify the underlying frequency and amplitude aspects of a complex signal, and then relate the response amplitude to its specific bandwidth frequency component contribution. The software has been used successfully in the laboratory to measure human visual attention via alpha power responses in the visually-normal population [28, 29].

**Procedures**

**VEP and alpha recordings**

The VEP and alpha recordings were obtained by using three standard, gold cup electrodes (i.e. active, reference and
Table I. Demographics of the mTBI subjects.

<table>
<thead>
<tr>
<th>Subject/age (years)/gender</th>
<th>Years since first injury</th>
<th>Type of injury: MVA/Sports/Fall/Assault</th>
<th>Visual symptoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1/30/F</td>
<td>5</td>
<td>Motor vehicle accident (MVA)</td>
<td>Visual motion sensitivity (VMS)</td>
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<tr>
<td></td>
<td></td>
<td>Loss of consciousness (LOC) for 10 minutes</td>
<td>Reading problems</td>
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<td></td>
<td></td>
<td></td>
<td>Photosensitivity</td>
</tr>
<tr>
<td>S2/38/F</td>
<td>6</td>
<td>Hit head during gymnastics</td>
<td>VMS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Altered state of consciousness (ASOC) for &lt;30 minutes</td>
<td>Reading problems</td>
</tr>
<tr>
<td>S3/26/M</td>
<td>7</td>
<td>Soccer injury (two injuries within a week)</td>
<td>VMS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ASOC for &lt;30 minutes</td>
<td>Reading problems</td>
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<td></td>
<td></td>
<td></td>
<td>Photosensitivity</td>
</tr>
<tr>
<td>S4/45/M</td>
<td>8</td>
<td>Involved in 8 military blast injuries</td>
<td>Visual-attention deficit</td>
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<tr>
<td></td>
<td></td>
<td>LOC for 5 minutes</td>
<td>VMS</td>
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<td></td>
<td></td>
<td></td>
<td>Reading problems</td>
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<td></td>
<td></td>
<td>Visual fatigue</td>
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<td></td>
<td></td>
<td></td>
<td>Visual-attention deficit</td>
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<tr>
<td>S5/24/F</td>
<td>6</td>
<td>Soccer injury</td>
<td>Visual-attention deficit</td>
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<tr>
<td></td>
<td></td>
<td>LOC for 10 minutes</td>
<td>VMS</td>
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<tr>
<td></td>
<td></td>
<td>ASOC for &lt;24 hours</td>
<td>Reading problems</td>
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<td></td>
<td></td>
<td></td>
<td>Distance perception problems</td>
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<td></td>
<td></td>
<td></td>
<td>Visual-attention deficit</td>
</tr>
<tr>
<td>S6/29/F</td>
<td>13</td>
<td>First injury due to snow-boarding accident and second hit head on the ground 5 years ago</td>
<td>Visual-attention deficit</td>
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<tr>
<td></td>
<td></td>
<td>LOC for 3 minutes</td>
<td>VMS</td>
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<tr>
<td></td>
<td></td>
<td>ASOC for &lt;30 minutes</td>
<td>Reading problems</td>
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<td></td>
<td></td>
<td></td>
<td>Distance perception problems</td>
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<td></td>
<td></td>
<td></td>
<td>Visual-attention deficit</td>
</tr>
<tr>
<td>S7/54/F</td>
<td>8</td>
<td>Hit head on the ground</td>
<td>Visual-attention deficit</td>
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<tr>
<td></td>
<td></td>
<td>LOC for 2 minutes</td>
<td>VMS</td>
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<tr>
<td></td>
<td></td>
<td>ASOC for &lt;30 minutes</td>
<td>Reading problems</td>
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<td></td>
<td></td>
<td></td>
<td>Photosensitivity</td>
</tr>
<tr>
<td>S8/39/F</td>
<td>4</td>
<td>MVA</td>
<td>Distance perception problems</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LOC for 2 minutes</td>
<td>Vestibular problems</td>
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<tr>
<td></td>
<td></td>
<td>ASOC for &lt;30 minutes</td>
<td>Migraine</td>
</tr>
<tr>
<td>S9/29/F</td>
<td>2</td>
<td>Hit by car 2 years ago and hit by heavy table lamp 1 year ago</td>
<td>Visual-attention deficit</td>
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<tr>
<td></td>
<td></td>
<td>LOC for 15 minutes</td>
<td>VMS</td>
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<td></td>
<td></td>
<td></td>
<td>Reading problems</td>
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<td></td>
<td></td>
<td></td>
<td>Distance perception problems</td>
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<td></td>
<td></td>
<td></td>
<td>Visual-attention deficit</td>
</tr>
<tr>
<td>S10/63/F</td>
<td>7</td>
<td>Iron bookcase fell on her head</td>
<td>Visual-attention deficit</td>
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<tr>
<td></td>
<td></td>
<td>LOC for 10 minutes</td>
<td>VMS</td>
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<td></td>
<td></td>
<td>ASOC for &lt;24 hours</td>
<td>Reading problems</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>Photosensitivity</td>
</tr>
<tr>
<td>S11/25/F</td>
<td>7</td>
<td>First injury due to water boarding sports accident; during second and third hit head on the ground</td>
<td>Visual-attention deficit</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LOC for 3 minutes</td>
<td>VMS</td>
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<td></td>
<td></td>
<td>ASOC for &lt;30 minutes</td>
<td>Reading problems</td>
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<td></td>
<td></td>
<td></td>
<td>Photosensitivity</td>
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<td></td>
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<td>Distance perception problems</td>
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<td></td>
<td></td>
<td></td>
<td>Visual-attention deficit</td>
</tr>
<tr>
<td>S12/26/F</td>
<td>1</td>
<td>MVA</td>
<td>Visual-attention deficit</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LOC for 5 minutes</td>
<td>VMS</td>
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<td></td>
<td></td>
<td>ASOC for &lt;30 minutes</td>
<td>Reading problems</td>
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<td></td>
<td></td>
<td></td>
<td>Photosensitivity</td>
</tr>
<tr>
<td>S13/65/F</td>
<td>7</td>
<td>Hit head on the ground 7, 3 and 1.5 years ago</td>
<td>Visual-attention deficit</td>
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<tr>
<td></td>
<td></td>
<td>LOC for 5 minutes</td>
<td>VMS</td>
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<td></td>
<td></td>
<td>ASOC for &lt;30 minutes</td>
<td>Reading problems</td>
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<td>Photosensitivity</td>
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<td></td>
<td></td>
<td>Distance perception problems</td>
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<td></td>
<td></td>
<td></td>
<td>Visual-attention deficit</td>
</tr>
<tr>
<td>S14/26/F</td>
<td>2</td>
<td>Hit back of head against sink</td>
<td>Visual-attention deficit</td>
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<td></td>
<td></td>
<td>LOC for 2 minutes</td>
<td>VMS</td>
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<td>Reading problems</td>
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<td>Distance perception problems</td>
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<td></td>
<td></td>
<td></td>
<td>Visual-attention deficit</td>
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<tr>
<td>S15/23/F</td>
<td>0.4</td>
<td>Hit head on the ground</td>
<td>Visual-attention deficit</td>
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<td></td>
<td></td>
<td>LOC for 5 minutes</td>
<td>VMS</td>
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<td></td>
<td></td>
<td>ASOC for &lt;45 minutes</td>
<td>Reading problems</td>
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<td></td>
<td></td>
<td>Photosensitivity</td>
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<tr>
<td>S16/26/M</td>
<td>3</td>
<td>Assaulted on head</td>
<td>Photosensitivity</td>
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<td></td>
<td></td>
<td>LOC for &lt;30 minutes</td>
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<td></td>
<td></td>
<td>ASOC for &lt;24 hours</td>
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</table>

The active, reference and ground electrodes were placed at the Oz, Fz, and Fp2 scalp positions, respectively. The active electrode was used to measure the response over the primary visual cortex (V1). To reduce test preparation time in clinic patients, the electrode placement was slightly modified from the International 10/20 system [48]. Before attaching the electrodes, the designated scalp regions were cleaned with alcohol wipes and abrasive gel and, lastly, conductive paste.
was used to attach the electrodes. Furthermore, to maintain the electrodes firmly in place, an elastic head band was applied.

The following three test conditions were used to measure the VEP responses, as well as to modulate the visual attentional state to assess the alpha power responses. Five trials for each of the three test conditions were performed. Test duration of each trial was 20 seconds. These protocols have been tested fully by the laboratory in visually-normal individuals [28]:

1. **VEP** [baseline, ‘eyes open (EO)’]: Conventional VEP test stimulus was employed (17°H × 15°V, 64 × 64 checkerboard pattern equivalent to 20 minute arc check size at 1 metre distance, 85% contrast, 74 cd m⁻² luminance, 1 Hz (2 reversals per second) temporal frequency, binocular viewing with spectacle correction). Per the manufacturer’s software, a small (0.25° radius) red, rotating, annular fixation target was presented in the centre of the test field to control fixation and accommodation, as well as to maintain visual attention. Subjects were instructed to fixate upon this small central target with minimal blinking to reduce any response artifacts. A chinrest/headrest assembly was used to reduce head movement and to maintain test distance. During this EO test condition, both the VEP and the alpha (8–13 Hz) power responses were measured. The EO condition was always performed first to assure VEP response normalcy. This was the baseline comparison condition, in which the alpha component is predicted to be markedly reduced due to the occurrence of visual ‘damping’ or ‘attenuation’, as described in the Introduction, due to signal asynchrony.

2. **Eyes-closed (EC) (‘relaxed’, reduced attentional state):** Subjects were instructed to sit comfortably in the chair and close their eyes. Then, they were asked to relax, and ‘clear their mind’ for 2 minutes before commencing the trials. This was the critical instruction to attain a reduced attentional state, which would allow for maximum alpha (8–13 Hz) power responsivity [28–30]. They were also instructed to imagine ‘gazing’ straight ahead where the central fixation target had been presented and not to move their eyes, to avoid any artifacts caused by saccadic eye movements. In this EC state, an increase in alpha power was predicted, as compared to both the EO and the ECNC conditions due to signal asynchrony [28, 30].

3. **Eyes-closed number counting (ECNC) (increased attentional demand):** Subjects were instructed to close their eyes, as in condition 2 (EC). However, they were also instructed to perform a mental arithmetic task [30]. Subjects were initially asked to count silently backwards in steps of seven, starting from 100, 96, 94, 92, and 90 for each of the five trials, respectively [28, 49]. Different numerical starting positions prevented memorization of the reverse order number sequences. This cognitive task was added to increase the attentional demand with the eyes closed. The alpha (8–13 Hz) power was assessed. Attenuation of alpha power was expected, as compared to the EO condition.

In addition, repeatability was assessed for each test condition. This was performed in four individuals with mTBI tested on two different days, two with and two without an attentional deficit.

**Adult ADHD self-report scale (ASRS)**

The Adult ADHD Self-Report Scale (ASRS) questionnaire was used as a screening tool to assess for a general attentional deficit in those with mTBI [50]. This was developed by the World Health Organization (WHO) to screen adults for attention-deficit/hyperactivity disorder. Test–re-test reliability for the ASRS was 0.87 [51], thus suggesting its validity. Validity was further confirmed by van de Glind et al. [52]. Sensitivity and specificity were 56.3 and 98.3, respectively [50]. It is comprised of 18 questions divided into two parts, with nine questions per part. Part A and Part B questions were related to inattention and hyperactivity/impulsivity, respectively. The subject is instructed to score each question based on ‘how they have felt and conducted themselves’ over the past 6 months. Each question had a rating scale ranging from 0–4, with 0 signifying ‘never felt and conducted’ to 4 signifying ‘very often felt and conducted’. The Part A and Part B values are scored separately. If the score for either Part A or Part B is in a range from 0–16, 17–23 and 24 or greater, the subject was unlikely, likely and highly likely to manifest an attentional and/or hyperactivity disorder, respectively. However, in the present study, only the Part A questionnaire scores were used related to general attention (see the Appendix).

**Visual search and attention test (VSAT)**

A second subjective visual attention test was performed in each individual with mTBI, namely the Visual Search and Attention Test or VSAT (©Psychological Assessment Resources, Inc., Lutz, FL). It is used in many optometric clinics and psychological practices [28, 39]. Test–re-test reliability for the VSAT was 0.95 [39], thus suggesting good validity. Sensitivity and specificity were 0.88 and 0.86, respectively [39]. It incorporates a visual search and cancellation task (e.g. find a blue colour letter ‘H’ and cross it out) that assesses the individual’s global, sustained, visual attention [39]. This test was performed binocularly at the individuals habitual near working distance (~40 cm), with refractive correction in place, in a quiet room per manual instructions. Following the two practice trials, the two test trials were performed. The subject was instructed to execute each trial in 60 seconds and to do so as rapidly and accurately as possible. An average of the two test trials was used to calculate the mean VSAT percentile score for each subject. These percentile scores were compared with the age-matched normative table provided in the VSAT manual.

**Alpha attenuation ratio (AR)**

The alpha AR is related to the human attentional state [28–30, 40]. Two different alpha attenuation ratios (ARs) were calculated, as described in detail earlier based on prior studies. The first was the alpha power (μV²) measured during the ‘eyes-closed (EC)’ condition divided by the alpha power measured during the ‘eyes-open (EO)’ condition [28, 29]. Willeford et al. [28, 29] found that an AR (EC ÷ EO) of 2.0 or greater suggested the presence of normal visual
attenuation. That is, there was considerable and normally-expected attenuation/suppression of the alpha activity in the ‘eyes-open’ condition as compared to the ‘eyes closed’ test condition. The second alpha AR was calculated as the alpha power (\(mV^2\)) measured during the ‘eyes-closed number counting (ECNC)’ condition divided by the alpha power measured during the ‘eyes-closed (EC)’ condition [28, 30]. Fuller [30] was the first to find, and Willeford et al. [28] confirmed and extended, that an AR (ECNC/EC) of <1.00 suggested the presence of normal attenuation. That is, there was considerable and normally-expected suppression of the alpha activity in the ‘eyes-closed number counting (ECNC)’ condition as compared to the ‘eyes closed (EC)’ test condition.

**Data analysis**

Several types of data analyses were performed. Five trials per test condition were done, and the average was used in the data analysis. First, the group mean VEP amplitude and latency were assessed. Second, the group mean of each alpha AR (i.e. EC ÷ EO and ECNC ÷ EO) at each individual alpha frequency (i.e. 8, 9, 10, 11, 12 and 13 Hz) was assessed, as well as the combined mean of each alpha AR (i.e. EC ÷ EO and ECNC ÷ EO) across all frequencies (i.e. 8–13 Hz). A one-way, repeated-measures ANOVA was used to assess the group data. In addition, three correlations were performed: between each subject’s ASRS Part A score and their alpha AR, between each subject’s VSAT percentile score and their alpha AR and between each subject’s ASRS and VSAT scores. Lastly, the coefficient of variation (CV = standard deviation ÷ mean) of the alpha wave responses was calculated to assess repeatability [28, 29, 45, 53]. GraphPad Prism 5 software was used to perform the analyses. Lastly, the data were segregated into those with vs without a self-reported attention deficit, as well as combined, for specific sub-group and group analyses.

**Results**

**VEP analysis: Group data \(n = 16\)**

The group mean VEP amplitude and latency (P100) were analysed. The group mean amplitude was 19.20 \(\mu\)V (SEM = ±2.38). The group mean latency was 108.86 ms (SEM = ±1.84). These amplitude and latency values were within normal limits for the laboratory [19, 40, 46]. This information was evaluated to confirm VEP response normalcy before assessing the attentionally-related alpha band component.

**Power spectrum analysis**

**mTBI with an attention deficit \(n = 11\)**

The group mean power spectrum value at each alpha band frequency (i.e. 8, 9, 10, 11, 12 and 13 Hz) across the three test conditions for individuals with mTBI and an attentional deficit are presented in Figure 2(A). A one-way ANOVA was performed for the factor of power for each alpha frequency across all three test conditions. There was no significant effect of power on the alpha band frequency \(F(5, 60) = 1.12, p > 0.05\). The group mean results were analysed using a one-way ANOVA for each alpha frequency comparing between conditions 1, 2 and 3 (Figure 2A). A significant difference between conditions was only found for the 11 Hz alpha frequency \(F(2, 30) = 4.04, p < 0.05\). At 11 Hz, the post-hoc Tukey test results revealed that the power (\(mV^2\)) value for the EO condition was significantly reduced with respect to the ECNC condition \(p < 0.05\).

**mTBI without an attention deficit \(n = 5\)**

The group mean power spectrum value at each alpha band frequency (i.e. 8, 9, 10, 11, 12 and 13 Hz) across the three test conditions for individuals with mTBI but without an attentional deficit are presented in Figure 2B. A one-way
ANOVA was performed for the factor of power for each alpha frequency across all three test conditions. There was a significant effect of power on the alpha band frequency \[F(5, 60) = 1.12, p < 0.05\]. The post-hoc Tukey test results revealed that the power (\(\mu V^2\)) value at 10 and 11 Hz was significantly larger than at 13 Hz \((p < 0.05)\). No other comparisons were significant \((p > 0.05)\).

The group mean results were analysed using a one-way ANOVA for each alpha frequency comparing conditions 1, 2 and 3 (Figure 2B). The one-way ANOVA found significant differences between conditions per the following alpha frequencies:

- **9 Hz**: There were significant differences between conditions \([F(2, 12) = 4.43, p < 0.05]\). The post-hoc Tukey test results revealed that the power (\(\mu V^2\)) value for the EO condition was significantly less than the EC condition \((p < 0.05)\). No other comparisons were significant \((p > 0.05)\).
- **10 Hz**: There were significant differences between conditions \([F(2, 12) = 17.87, p < 0.05]\). The post-hoc Tukey test results revealed that the power (\(\mu V^2\)) value for the EO and ECNC conditions were significantly less than for the EC condition \((p < 0.05)\). No other comparisons were significant \((p > 0.05)\).
- **11 Hz**: There were significant differences between conditions \([F(2, 12) = 7.35, p < 0.05]\). The post-hoc Tukey test results revealed that the power (\(\mu V^2\)) value for the EO condition was significantly less than for the EC and the ECNC conditions \((p < 0.05)\). No other comparisons were significant \((p > 0.05)\).
- **12 Hz**: There were significant differences between conditions \([F(2, 12) = 9.24, p < 0.05]\). The post-hoc Tukey test results revealed that the power (\(\mu V^2\)) value for the EO condition was significantly less than for the EC and the ECNC conditions \((p < 0.05)\). No other comparisons were significant \((p > 0.05)\).

### Alpha attenuation ratio (AR): Individual alpha frequencies

#### Eyes-closed ÷ Eyes-open (EC ÷ EO)

The group mean AR for each alpha frequency (i.e., 8, 9, 10, 11, 12 and 13 Hz) for individuals with mTBI and an attentional deficit is presented in Figure 3(A). The mean AR at each alpha frequency was lower than the normative AR value of \(>2.00\) \([28, 29]\). The mean alpha AR ranged from 0.806–1.36. A one-way, repeated-measures ANOVA was performed for the factor of AR at each alpha frequency. There was a significant effect of AR on the alpha frequencies \([F(5, 10) = 3.36, p < 0.05]\). The post-hoc Tukey test results revealed that the AR at 10 Hz was significantly lower than the AR at 13 Hz \((p < 0.05)\). No other comparisons were significant \((p > 0.05)\).

The group mean AR for each alpha frequency (i.e., 8, 9, 10, 11, 12 and 13 Hz) for individuals with mTBI but without an attention deficit is presented in Figure 3(B). The mean AR at 9, 10, 11 and 12Hz was \(\geq2.00\), which was normal \([28, 29]\). The mean alpha AR ranged from 1.59–3.92. A one-way, repeated-measures ANOVA was performed for the factor of AR at each alpha frequency. There was a significant effect of AR on the alpha frequencies \([F(5, 4) = 4.46, p < 0.05]\). The post-hoc Tukey test results revealed that AR at 8 and 13 Hz was significantly lower than the AR at 11 Hz \((p < 0.05)\).

#### Eyes-closed number counting ÷ Eyes-closed (ECNC ÷ EC)

The group mean AR for each alpha frequency (i.e., 8, 9, 10, 11, 12 and 13 Hz) for individuals with mTBI and an attentional deficit is presented in Figure 4(a). The mean AR at each alpha frequency was higher than the normative AR value of \(<1.00\) \([28, 30]\). The mean alpha AR ranged from 1.27–2.24. A one-way, repeated-measures ANOVA was performed for the factor of AR at each alpha frequency. There was no significant effect of AR on the alpha frequencies \([F(5, 10) = 1.28, p > 0.05]\).

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![Figure 3](image-url)

Figure 3. The group mean alpha attenuation ratio (AR) (EC/EO) for each alpha frequency. Plotted is the mean +1 SEM. (A) Individuals with mTBI and an attention deficit, (B) Individuals with mTBI without an attention deficit. Symbols as in Figure 2.
The group mean AR for each alpha frequency (i.e. 8, 9, 10, 11, 12 and 13 Hz) for individuals with mTBI but without an attentional deficit is presented in Figure 4(B). The mean AR at 8, 9, 10, 11 and 12 Hz was \$5.1.00\$, which was normal \[28, 30\]. The mean alpha AR ranged from 0.59–1.10. A one-way, repeated-measures ANOVA was performed for the factor of AR at each alpha frequency. There was a significant effect of AR on the alpha frequencies \[F(5, 4) = 2.92, p < 0.05\]. The post-hoc Tukey test results revealed that the AR at 10 Hz was significantly lower than the AR at 13 Hz \(p < 0.05\). No other comparisons were significant \(p > 0.05\).

Alpha attenuation ratio (AR): Combined across the alpha frequency band (8–13 Hz)

Eyes-closed \(\div\) Eyes-open (EC \(\div\) EO)

The AR combined across the alpha frequency band (i.e. from 8–13 Hz) for each individual with mTBI and an attentional deficit is presented in Figure 5(A). The AR combined across the alpha frequency band for each individual was lower than the mean normative AR value of \(\geq 2.00\) [28, 29]. The group mean AR combined across the alpha frequency band was 1.01 (SEM = 0.07), with a range from 0.62–1.33.

The AR combined across the alpha frequency band (i.e. from 8–13 Hz) for each individual with mTBI but without an attentional deficit is presented in Figure 5(B). The AR combined across the alpha frequency band for each individual was \(\geq 2.00\), which was normal [28, 29]. The group mean AR combined across the alpha frequency band was 2.19 (SEM = 0.03) with a range from 2.07–2.18.

An unpaired, two-tailed, \(t\)-test was performed between those having mTBI with vs without an attentional deficit for the AR combined across the alpha frequency band. The results revealed a significant difference \(t(14) = 9.78, p < 0.05\). It was higher in the mTBI sub-group without an attentional deficit.
Eyes-closed number counting = Eyes-closed (ECNC ÷ EC)

The AR combined across the alpha frequency band (i.e. from 8–13 Hz) for each individual with mTBI and an attentional deficit is presented in Figure 6(A). The AR combined across the alpha frequency band for most individuals (except subjects #12 and 13) was higher than the normative AR value of <1.00 [28, 30]. However, in these two subjects, the error bars (+SD) crossed into the normal range. The group mean AR combined across the alpha frequency band was 1.79 (SEM = 0.96), with a range from 0.86–4.33.

The AR combined across the alpha frequency band (i.e. from 8–13 Hz) for each individual with mTBI but without an attentional deficit is presented in Figure 6(B). The AR combined across the alpha frequency band for each individual was 1.00, which was normal [28, 30]. The group mean AR combined across the alpha frequency band was 0.806 (SEM = 0.02), with a range from 0.71–0.86.

An unpaired, two-tailed, t-test was performed between those having mTBI with vs without an attentional deficit for the AR combined across the alpha frequency band. The results revealed a significant difference [t(14) = 2.24, p < 0.05]. It was smaller in mTBI without an attentional deficit.

Adult ADHD self-report scale (ASRS)

The Part A questionnaire scores for the ASRS test, which were related to general attention for each subject, are presented in Table II. As mentioned earlier, if the scores were in a range from 0–16, 17–23, and 24 or greater the subject was unlikely, likely, and highly likely to manifest an attentional deficit, respectively. The mean score in those having mTBI with a self-reported attentional deficit (n = 11) was 22.81 (SEM = 0.97), with a range from 17–28. In contrast, the mean score in those having mTBI without a self-reported attentional deficit (n = 5) was 12.4 (SEM = 1.36), with a range from 8–16.

An unpaired, two-tailed, t-test was performed between those having mTBI with and without an attentional deficit per their ASRS score. There was a significant difference [t(14) = 6.04, p < 0.05]. It was higher in those having mTBI with an attentional deficit.

Visual search and attention test (VSAT)

The VSAT percentile scores for each subject are presented in Table II. The mean VSAT percentile score in those having mTBI with a self-reported attentional deficit (n = 11) was 54.72 (SEM = 10.95) with a range from 1–93. The mean score in those having mTBI but without a self-reported attentional deficit (n = 5) was 68.8 (SEM = 14.54) with a range from 12–95. Subjects S10 and S9 had borderline 6th and 12th percentile scores, respectively. Subject S12 had a frank abnormal 1st percentile score. An unpaired, two-tailed,
t-test was performed between those having mTBI with and without a visual attentional deficit per the VSAT percentile scores. There was no significant difference [t(14) = 0.73, p > 0.05].

Correlations
Linear regression analysis was used to assess all of the correlations between the different parameters for all individuals with mTBI (n = 16), as described below.

Alpha AR and adult ADHD self-report scale (ASRS) score
Correlation between the AR for the EC ÷ EO condition and the ASRS score at each alpha frequency was performed. There were significant correlations at 8, 9, 10, 11 and 12 Hz (r = 0.62–0.83, p < 0.05), being highest at 9, 10 and 11 Hz (r = 0.73–0.83). Similarly, a significant correlation was found between the AR for the EC ÷ EO condition combined across the alpha frequency band and the ASRS scores (r = 0.76; p < 0.05).

Correlation between the AR for the ECNC ÷ EO condition and the ASRS score at each alpha frequency was quantified. There was a significant correlation only at 8 Hz (r = 0.53, p < 0.05). A significant correlation was not found between the AR for the ECNC ÷ EC condition combined across the alpha frequency band and the ASRS scores (p > 0.05).

Alpha AR and VSAT percentile score
Correlation between the AR for the EC ÷ EO condition and the VSAT percentile scores at each alpha frequency, as well as across the alpha frequency band, was quantified. No significant correlations were found (p > 0.05).

Correlation between the AR for the ECNC ÷ EC condition and the VSAT percentile scores at each alpha frequency, as well as across the alpha frequency band, was quantified. No significant correlations were not found (p > 0.05).

ASRS and VSAT scores
Correlation between the ASRS score and the VSAT score was performed. It was not significant (r = -0.14, p > 0.05).

Repeatability
Repeatability was assessed after a period of 2 weeks in two individuals with and two individuals without an attentional deficit with respect to power spectrum values across all three conditions for each alpha band frequency (i.e. 8, 9, 10, 11, 12 and 13 Hz), amplitude and latency. The coefficient of variation (CV) analysis was used. CV values across all parameters were extremely small in both groups. The median value was 0.09, with a range from 0.003–0.58.

Discussion
The present investigation demonstrated for the first time that the VEP could be used to detect and assess objectively for a visual attentional deficit in the mTBI population and, furthermore, differentiate between those having mTBI with and those without a visual attentional deficit. The visual attentional deficit could be detected as early as the primary visual cortex (V1). More specifically, the attenuation ratio (AR) (i.e. EC ÷ EO and ECNC ÷ EC) at each alpha band frequency was able to differentiate objectively between those with and without an attentional deficit. Similar results were also found when the AR was combined across the alpha frequency band (8–13 Hz). Lastly, the objective VEP alpha frequency findings were significantly correlated with the subjective ASRS neuropsychological general attention questionnaire scores.

The findings of the current study confirmed, clarified and extended the results of previous studies [28, 29, 40, 54, 55]. First, the present findings extended the results of Willeford et al. [28, 29], who predicted that individuals with mTBI and an attentional deficit would manifest an abnormal AR, as found in the present study. In addition, in the current investigation, three individual alpha band frequencies (i.e. 9, 10 and 11 Hz) provided highly reliable information regarding the visual attentional state in the mTBI population. The same alpha band frequencies were found to provide highly reliable, visual attentional information in the visually-normal adult population [28, 29]. Thus, these specific frequencies were high-yield parameters in both populations. Second, the present study results were in agreement with the recent Yadav et al. [40] study. They found an abnormal EC ÷ EO AR at both the individual and combined alpha frequencies before oculomotor vision rehabilitation (OVR) in a sample mTBI population. Following successful OVR, however, the AR significantly increased, thus reflecting concomitant increased and enhanced visual attention. This confirms the speculation of many that embedded in all OVR is visual attentional training [42, 43]: one must be able to attend visually to and detect progressively smaller changes in magnitude of target blur, disparity and displacement as part of the oculomotor rehabilitative training process. Lastly, the present study suggests that the processing of visual attention occurs as early as the primary visual cortex (V1) in the mTBI population, as well as in the visually-normal population [28, 29], with this information later being transmitted to higher cortical areas (e.g. parietal, temporal) for further visual information processing, as suggested by Somers et al. [54] and provided in more detail by Kastner and Ungerleider [55], as briefly described below. More specifically, visual attentional information from V1 is transmitted to the higher cortical levels by the ventral and dorsal pathways. The ventral pathway is involved in visual attentional processing related to identification of object attributes (e.g. colour), which occurs in the temporal lobe. In contrast, the dorsal pathway is involved in visual attentional processing related to the spatial relations between different objects, as well as their motion in the visual world, which occurs in the parietal lobe.

Alpha attenuation ratio (AR)
The present findings support the proposed hypothesis: individuals with mTBI and a visual attentional deficit did not exhibit attenuation of the alpha band power during the EO and ECNC conditions, as compared to the EC condition. No significant differences were found across these three conditions. In contrast, those with mTBI but without an attentional deficit did. Furthermore, the mean EC ÷ EO AR
was found to be abnormal (i.e. ≤2) at each alpha band frequency in those with an attentional deficit. In contrast, it was within normal limits (i.e. ≥2) at the 9, 10, 11 and 12 Hz alpha frequencies in individuals without an attentional deficit. Similar results were found when the EC ÷ EO AR was combined across the alpha frequency band (8–13 Hz) in both mTBI sub-groups.

The mean ECNC ÷ EC AR was also found to be abnormal (i.e. >1) at each alpha band frequency in those with an attentional deficit. In contrast, it was within normal limits (i.e. <1) at the 8, 9, 10 and 11 Hz alpha frequencies in those individuals without an attentional deficit. Similar findings were found when the ECNC ÷ EC AR was combined across the alpha frequency band (8–13 Hz) in both mTBI sub-groups. Therefore, these findings clearly demonstrate that the VEP could be used as an objective, rapid and repeatable technique to detect and assess the attentional state in those with mTBI.

**Subjective attention tests (ASRS and VSAT)**

The ASRS questionnaire was found to be valuable in differentiating between those with and without an attentional deficit in the mTBI population. The ASRS questionnaire scores for all individuals with mTBI having a self-reported attentional deficit (n = 11) were in the abnormal range (17–28). Moreover, the ASRS scores for all individuals with mTBI but without having a self-reported attentional deficit (n = 5) were in the normal range (8–16). This suggests that the ASRS questionnaire was an excellent predictor of an attentional deficit in the mTBI population (100%). In contrast, the VSAT was not a good predictor (18%). Furthermore, the VSAT percentile scores were not able to differentiate these two mTBI sub-groups regarding presence or absence of an attentional deficit, and it did not correlate with the ASRS scores.

**Correlation between objective and subjective findings**

The aforementioned objective findings were in agreement with the subjective ASRS questionnaire scores. These scores were significantly correlated with the EC ÷ EO AR at each of the individual alpha band frequencies (except for 13 Hz). In contrast, the ASRS score was only significantly correlated with the ECNC ÷ EC AR at the 8 Hz alpha band frequency. Similarly, a correlation was found when the EC ÷ EO AR was combined across the alpha band frequencies (8–13 Hz); however, again there was no correlation with the ECNC ÷ EC AR. Taken together, these findings suggest that the EC ÷ EO AR was a much more robust and sensitive indicator for detection of a visual attentional deficit in this population as compared with the ECNC ÷ EC AR. Lastly, these correlations suggest that the VEP findings at the V1 level were related to responses at higher cortical levels, as the subjective responses likely involve higher cortical attentional areas (e.g. frontal) [56].

In contrast, the objective VEP alpha frequency findings were not correlated with the VSAT percentile scores. The present VSAT results were also not in agreement with that of Willeford et al. [28], who found specific frequency correlations; however, their test population was visually-normal and not mTBI. Another possible reason for this difference might be due to larger spread of AR values in their visually-normal population, as compared to the present mTBI population, which would yield more likelihood for obtaining a significant correlation [57].

**Neurophysiological mechanism**

A possible neurophysiological mechanism underlying these findings is based on the concept of synchronous and asynchronous neuronal activity. Such activity occurs at the primary visual cortex (V1) level during modulation of one’s attentional state (e.g. eyes-closed as compared to the eyes-open condition).

What might occur during the EC relaxed/low attentional demand condition? Klimesch [26] and others [58, 59] suggested that, in individuals with normal attention, synchronous neuronal activity occurs. This was presumably due to oscillation of a large number of neurons having the same phase and frequency. These synchronous oscillations can be appreciated quantitatively as reflective of increased alpha band power. This oscillatory activity is believed to ‘block’ information processing from occurring. In contrast, it was suggested that, in those individuals with mTBI and an attentional deficit, asynchronous activity occurs during the EC (‘relaxed’) attentional state and, thus, information processing cannot be ‘blocked’; that is, information processing continues to occur unimpeded. The asynchronous neuronal activity would cause attenuation or suppression/damping of the alpha band power via signal cancellation [60]. The same is true for the ECNC condition, but to a lesser degree.

The opposite is believed to occur in the EO condition. In individuals with normal attention, asynchronous neuronal activity is believed to occur during the EO condition. This asynchrony is believed to be due to oscillation of a large number of neurons with different phases and frequencies, which occurs due to processing of the more visually-based information. This asynchrony causes attenuation of the alpha band power, again via signal cancellation [60]. In individuals with mTBI and an attentional deficit, asynchronous activity occurs during all three conditions and, thus, presence of marked attenuation. The findings of the present study are consistent with the proposed mechanism of Klimesch [26] and others [58, 59].

**Proposed VEP attentional test protocol**

Based on the results of the present study and others conducted in the laboratory [28, 29, 40], the following attentional test protocol is proposed for clinic use in the mTBI population:

1. **Case history**: A detailed case history should be taken regarding attention.

2. **Subjective test**: The Adult ADHD Self-Report Scale (ASRS) Part A questionnaire should be used as a screening tool to assess for presence of an attentional deficit.

3. **Objective test**: The following two VEP test conditions should be performed to assess for VEP normalcy, as well as to quantify the alpha band power and AR parameter with regard to visual attention:
   - (a) Eyes open (EO); and
   - (b) Eyes-closed (EC).
(4) Number of trials: 5 trials (each 20 seconds) should be performed for each test condition and averaged.

Quantification of the EC ÷ EO AR should be performed. If the AR is ≥2, mainly at the 9, 10 and 11 Hz high-yield alpha band frequencies, this would suggest normal attention; if not, it would suggest presence of a visual attentional deficit. If the subjective and objective test results agree and are consistent with the case history findings, the patient would likely have an attentional deficit. This proposed VEP visual attentional protocol may prove helpful to clinicians in assessing visual attention objectively, rapidly, reliably and quantitatively.

Clinical implications

There are several important clinical implications based on the findings of the present study. First, there is a high prevalence (~50%) of visual/general attentional deficits in the mTBI population [61]. Second, the AR parameter was related to attentional state and attenuation ability. Thus, it may be a reliable indicator and clinical barometer of visual attention. The objectively-based AR should be compared with the patient’s subjective ASRS Part A scores. This would help the clinician make a more accurate diagnosis regarding a patient’s attentional state. Third, due to its objective nature, the VEP protocol may be extended to assess visual attention in cognitively-impaired individuals [62] and non-verbal patients [63], as well as paediatric patients with attention deficit hyperactivity disorder (ADHD) [64]. Lastly, the proposed testing would also allow clinicians to evaluate objectively the effect of a visual intervention incorporating an attentional component [40].

Study limitations

There were three possible study limitations. First, sample size was relatively small. However, the effect was very robust (100%). Second, this study included only those with mTBI. It should be extended to those with moderate and severe TBI. Third, other tests for concussion such as the Sports Concussion Assessment Tool (SCAT2) [65], which incorporates the GCS test and others, could be used for broader assessment and for possible correlation with objective findings, such as the VEP.

Conclusions

This is the first time the clinical VEP technique has been used to detect and assess a visual attentional deficit at the V1 cortical level in the mTBI population. It was accomplished by modulating the attentional state and quantifying the outcome via the AR power spectrum analysis parameter. The AR was found to be able to detect and differentiate between mTBI with and without an attentional deficit. Furthermore, these objective findings were in agreement with the subjective Part A ASRS scores. This test protocol should be extended to other ‘special’ populations having visual and general attentional problems.

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Declaration of interest

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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Appendix: Part A questionnaire related to attention

(1) How often do you make careless mistakes when you have to work on a boring or difficult project?
(2) How often do you have difficulty keeping your attention when you are doing boring or repetitive work?
(3) How often do you have difficulty concentrating on what people say to you, even when they are speaking to you directly?
(4) How often do you have trouble wrapping up the final details of a project, once the challenging parts have been done?
(5) How often do you have difficulty getting things in order when you have to do a task that requires organization?
(6) When you have a task that requires a lot of thought, how often do you avoid or delay getting started?
(7) How often do you misplace or have difficulty finding things at home or at work?
(8) How often are you distracted by activity or noise around you?
(9) How often do you have problems remembering appointments or obligations?