

Texture segregation in traumatic brain injury—a VEP study

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Abstract

Visual evoked potentials (VEPs) were recorded to textures segregated by gradients in orientation or motion. Recordings were obtained in traumatic brain-injured (TBI) subjects and in normal controls. We analyzed both the low-level VEPs (lVEPs) evoked by homogenous stimuli, as well as the components associated with texture segregation (tsVEP) obtained through an appropriate linear combination. Our results suggest that the tsVEP, presumably higher up in the visual processing chain than the lVEP, is sensitive to TBI and can reveal further information as to the nature of possible information processing deficits after TBI. It could also help quantify cortical damage that is not revealed with more standard clinical tools.

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1. Introduction

Previous studies have shown that texture segregation, which is closely related to pop-out and is a fundamental mechanism involved in segregating a figure from its background (Julesz & Bergen, 1983), can be detected with visual evoked potentials (VEPs). This mechanism relies on visual dimensions like luminance, stereo, color, orientation, motion and spatial frequency. Electrophysiological studies of normal texture segregation have revealed a negative component peaking at around 150–200 ms in response to textured stimuli (Bach &

Meigen, 1992, 1997). This component is thought to originate from VI and to reflect the integration of information from associative visual areas (V2 and V3) via intracortical retroaction circuits towards V1 (Bach & Meigen, 1992, 1997; Lamme, Van Dijk, & Spekreijse, 1992). The tsVEP technique is of interest because it provides an intermediate measure of visual processing between low-level VEPs (lVEPs), which culminate at around 100 ms, and cognitive ones which peak typically after 300 ms.

Since the tsVEP is thought to reflect a complex level of visual information processing, it could be used to provide further information on visual processing efficiency as well as on more global information processing integrity in the brain. However, VEPs obtained to texture segregation are relatively recent and have not yet been studied in clinical populations. A patient population to which such a technique could be applied to better understand its functional consequences is traumatic brain

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injury (TBI) (Lachapelle, McKerral, & Bach, 2002). TBI is one of the main causes of acquired brain damage in human adults (Marion, 1998). It is usually the result of acceleration–deceleration and rotational forces which cause damage at neuronal and axonal levels, which is mostly diffuse in nature (Levin et al., 1987; Oppenheimer, 1968; Uzzell, Dolinskas, & Wiser, 1990). TBI patients present many sequelae at the cognitive level (Walsh, 1985) and visual function is often affected (Cohen & Rein, 1992; Gianutsos, Ramsey, & Perlin, 1988; Padula, Argyris, & Ray, 1994). Given that at least half of the cerebral cortex contributes to the analysis of the visual world, it is not surprising that, because of the lesion-producing mechanisms involved, many TBI patients present such difficulties in the visual domain. The most frequent symptoms are transient diplopia, binocular and oculomotor dysfunctions, accommodation problems, instability of the spatial environment, visual fatigue and photophobia (Cohen & Rein, 1992; Fraco & Fells, 1989). However, these symptoms are often difficult to objectify on neuro-ophthalmological examination because of their transient nature and because they are linked to central deficits in information processing. It is thus important to develop objective methods which can help characterize such information processing deficits since this could lead to more specific treatment (i.e. rehabilitation).

Previous electrophysiological studies of TBI patients have usually investigated only one level (primary) of visual information processing with few stimulation parameters and have yielded mixed results (Gaetz & Bernstein, 2001; Gaetz & Weinberg, 2000; Papathanasopoulos et al., 1994; Rizzo, Pierelli, Pozzessere, Floris, & Morocutti, 1983; Werner & Vanderzandt, 1991). Consequently, the use of VEPs reflecting more complex processing of visual attributes (i.e. tsVEP) could help to better objectify and describe deficits in information processing which can occur following TBI.

2. Methods

2.1. Subjects

Standard low-level visual evoked potentials (lVEPs) and VEPs associated with texture segregation (tsVEPs) were recorded in 13 patients having sustained a TBI (4 females, 9 males), ranging in age from 19 to 52 years old (mean: 37.8 years). Patients were recruited upon their arrival in the TBI program at the Centre de Réadaptation Lucie-Bruneau in Montréal. Subjects were tested between 2 and 39 months post-TBI. TBI severity was from mild to severe (5 mild, 5 moderate, 3 severe). The criteria used to determine TBI severity are those used by the neurotrauma continuum of services in Québec and based on the American Congress

of Rehabilitation Medicine definition of TBI (Kay et al., 1993).

VEPs were also obtained in 13 normal control subjects (10 females, 3 males), ranging in age from 22 to 52 years (mean: 29.0 years). All subjects had best-corrected visual acuity of 20/20 or better and had no visual pathology, other than possible post-TBI visual symptoms, on ophthalmological exam. The research followed the Tenets of the declaration of Helsinki, was approved by the Centre de Recherche Interdisciplinaire en Réadaptation's ethical committee and informed consent was obtained from all subjects after the nature and possible consequences of the study had been fully explained.

2.2. Electrophysiology

Signals were recorded using a single active gold-cup electrode installed at Oz following the International Society of Clinical Electrophysiology in Vision (ISCEV) standards in keeping with the 10/20 system (Harding, Odom, Spileers, & Spekrijse, 1996). An electrode placed on the forehead served as reference and the ground was attached to one earlobe. Signals were low pass digitally filtered at 40 Hz. Electrode impedance was maintained under 5 k Ω (Grass impedance meter, E2M5 model).

2.3. Stimuli

The stimuli were presented using a Macintosh G4 computer with a resolution of 800 \times 600 pixels at a frame rate of 75 Hz. They were generated by the EP-2000 Freiburg evoked potentials system (Bach, 2000–2003; Bach, 2001), and viewed on a ViewSonic monitor installed 1.14 m from the subject. The screen covered 19 $^\circ$ horizontal \times 18 $^\circ$ vertical and luminance was set at 45 cd/m 2 . All subjects were tested using orientation- or motion-defined stimuli to obtain lVEPs and tsVEPs. In order to ensure a high level of attention, subjects were asked to fixate a dot in the center of the screen and to signal the appearance of a number in the center of the dot during the complete recording session, which lasted about 15–20 min. For each stimulus arrangement, 40 sweeps were recorded and averaged on-line and the two similar responses recorded for both low-level VEPs and texture-segregation VEPs ensured reproducibility of the evoked potentials.

For the orientation condition, the stimuli were of an on-off type and luminance of the screen was maintained constant when the stimulus was off. Oriented line segments of 7.3 $^\circ$ width were presented in four different arrangements, separated by a grey condition (Fig. 1a). All lines were oriented in the same direction for two homogeneous stimuli (from which were obtained the lVEP), and with a 90 $^\circ$ orientation gradient for two textured ones (from which were derived the tsVEP). The

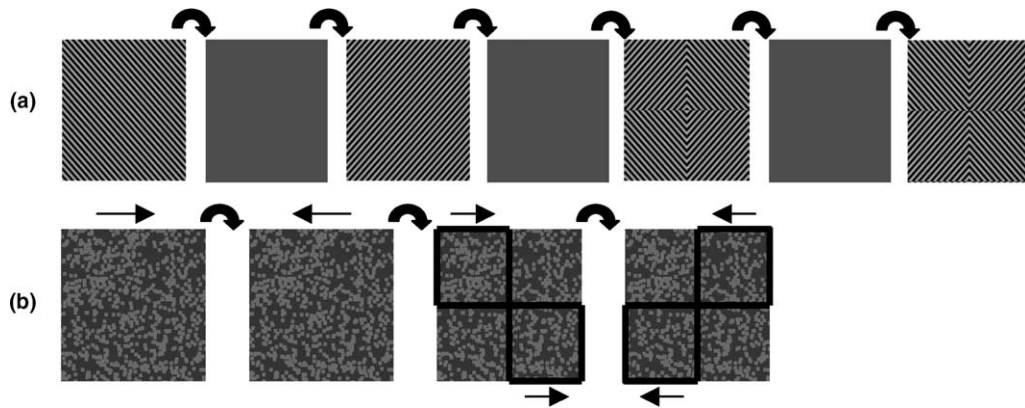


Fig. 1. Example of stimuli for the orientation condition (a) and the motion condition (b).

contrast was set at 98% and the shifts between stimuli occurred at a rate of 1 Hz. Patterns appeared for 300 ms followed by a grey screen for 700 ms.

For the motion condition, bright squares of 0.1° on a dark background were used. The fully correlated motion of all squares in the same direction constituted the homogenous stimuli (lIVEP), and motion of half of the squares in a checkerboard arrangement evoked the tsVEPs (Fig. 1b). The contrast was set at 30% and shifts between stimuli occurred at a rate of 1 Hz.

2.4. Data analysis

A different VEP response was obtained for each of the four different stimuli in the sequence; two low-level and two textured ones (orientation: Fig. 2; motion: Fig. 3). Rationale for the data analysis is the assumption that the tsVEP is composed of a texture-segregation component added onto response (lIVEP). In order to

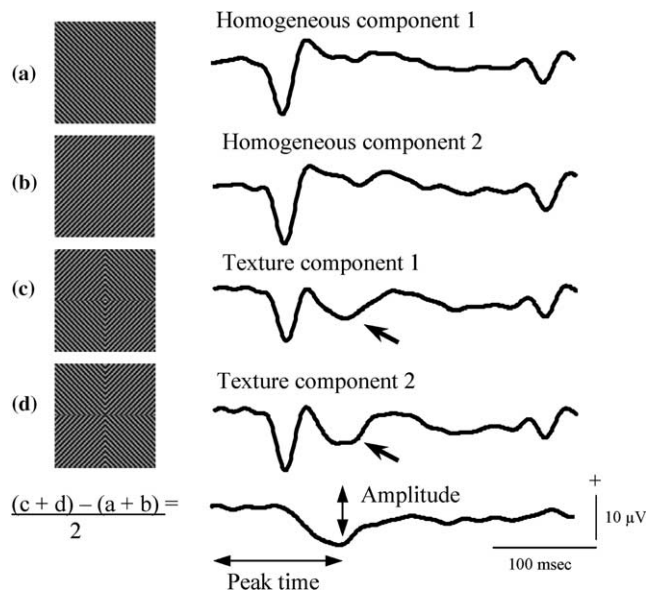


Fig. 2. Method for extracting the tsVEP in the orientation condition.

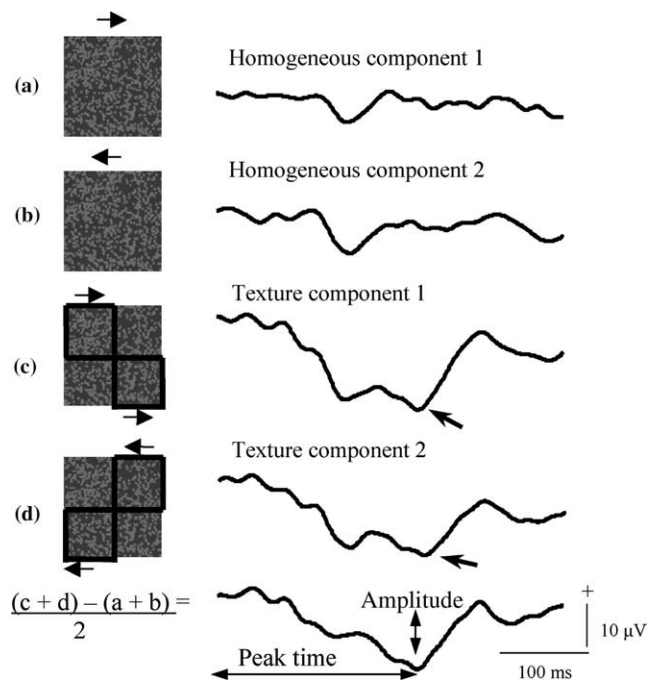


Fig. 3. Method for extracting the tsVEP in the motion condition.

separate the response associated with from the low-level VEP, a linear combination was calculated. For the lIVEPs, the mean of the two VEPs obtained to the homogenous stimuli was derived. For the tsVEP, since the textured stimuli are made of half stimuli a + half stimuli b, assuming linearity we subtract the homogeneous responses (a + b) from the mixed VEP conditions (c + d) and divide the result by 2. The lIVEPs are thus eliminated and the resulting negative potential reflects the tsVEP response (Bach & Meigen, 1990, 1992; Bach, Schmitt, Quenzer, Meigen, & Fahle, 2000; Lamme et al., 1992). This resulting potential was analyzed in amplitude (from baseline to the most negative point) and in peak time (from start of stimulation to the most negative point) (Figs. 2 and 3). Means and standard deviations were calculated and a mixed design two-way ANOVA

was used in order to test for any statistically significant differences. The statistical differences were analyzed using Tukey's post hoc test.

3. Results

Figs. 2 and 3 respectively show examples of responses, obtained in a normal subject, to all four stimuli presented in the orientation condition and to all four stimuli presented in the motion condition. The first two responses (a and b) are low-level VEPs (lIVEPs), those which are associated with mechanisms specific for each visual dimension, for example here orientation (Fig. 2) or motion (Fig. 3). The other two responses (c and d) represent the texture components (tsVEP) added to the low-level responses. The texture-segregation component is thus superimposed on the lIVEP. By eliminating the lIVEP using the function described above, the resulting negative component reflects the averaged texture-segregation mechanisms.

A clear tsVEP response could be isolated for all normal and TBI subjects for both orientation and motion conditions. The texture responses in the two conditions are composed of a negative peak followed by a positive peak, but are of slightly different morphology. As seen in Fig. 4, the resulting tsVEP responses obtained to orientation or motion are reproducible between subjects.

In order to further characterize information processing deficits present after TBI and also to evaluate the clinical applicability of the tsVEP technique, lIVEP and tsVEP data obtained in TBI and normal control subjects for orientation and motion conditions were statistically compared and the mean results are graphed in Fig. 5.

First, for both normal controls and TBI subjects, the lIVEP obtained in the orientation condition is of significantly larger amplitude (controls: $F=54.55$, $p<0.0001$; TBI: $F=42.04$, $p<0.0001$) and shorter peak time (controls: $F=19.26$, $p<0.0001$; TBI: $F=19.35$, $p<0.0001$) than that obtained in the motion condition. Our results also demonstrate differences between the orientation

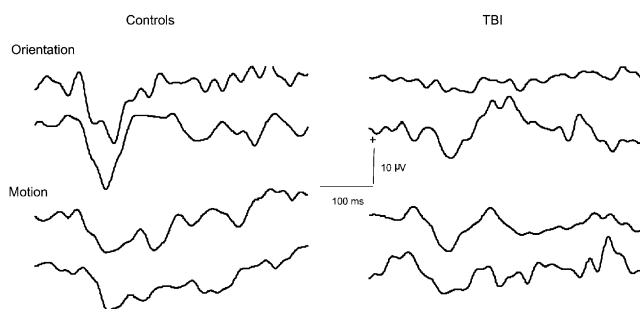


Fig. 4. Typical examples of tsVEPs obtained from two normal control and two TBI subjects.

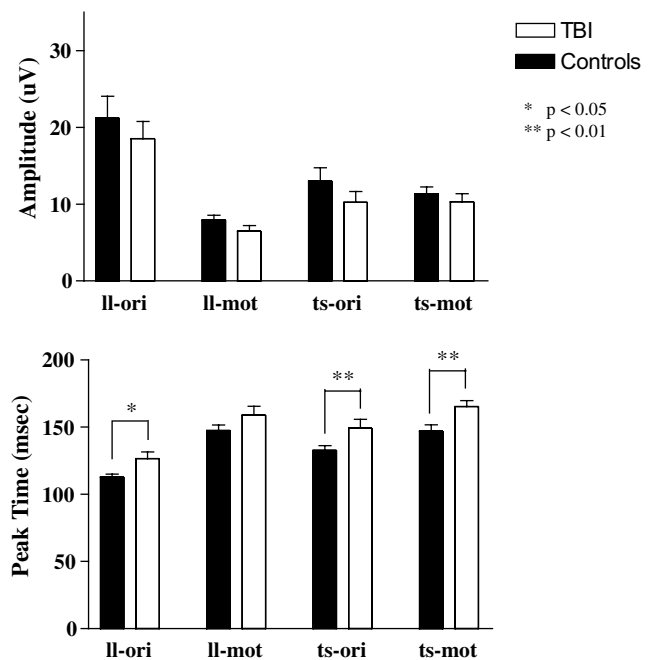


Fig. 5. Mean group results (+1 SEM) for orientation and motion lIVEPs and tsVEPs obtained from normal control and TBI subjects. Asterisk indicate significant differences between TBI and normal control subjects.

and motion conditions for the textured stimuli. In fact, for control subjects as well as for TBI subjects, the orientation tsVEP peaks significantly earlier (controls: $F=3.68$, $p<0.05$; TBI: $F=5.39$, $p<0.05$) than the motion tsVEP. However, there are no such significant amplitude differences for the tsVEP between orientation and motion conditions in TBI ($F=0.00$, $p=0.9760$) or normal control subjects ($F=0.99$, $p=0.3221$).

Second, in the orientation condition the lIVEP of normal controls and TBI subjects is of significantly larger amplitude (controls: $F=21.91$, $p<0.0001$; TBI: $F=19.81$, $p<0.0001$) and shorter peak time (controls: $F=5.48$, $p<0.05$; TBI: $F=9.04$, $p<0.01$) than the tsVEP. Findings are different between the lIVEP and tsVEP in the motion condition, where there are no significant differences for TBI or control subjects in peak time (controls: $F=0.02$, $p=0.8986$; TBI: $F=0.87$, $p=0.3553$) or for normal subjects in amplitude ($F=2.92$, $p=0.0921$). In contrast, in TBI subjects the amplitude of the motion lIVEP is significantly smaller than that of the motion tsVEP ($F=4.26$, $p<0.05$).

Differences between normal control subjects and those having sustained a TBI were also statistically compared. For the amplitude, the TBI group tends to show a decrease in amplitude compared to normal, but which do not reach statistical significance for the orientation lIVEP ($F=2.22$, $p=0.1410$), the motion lIVEP ($F=0.28$, $p=0.6001$), the orientation tsVEP ($F=1.33$, $p=0.2531$) or the motion tsVEP ($F=0.09$, $p=0.7664$). In contrast, when we compare peak time values, we find

a significant increase in peak time for the orientation lIVEP ($F=4.59$, $p<0.05$), the orientation tsVEP ($F=6.00$, $p<0.01$) and the motion tsVEP ($F=6.62$, $p<0.01$). The motion lIVEP condition did not yield a significant peak time difference between controls and TBI subjects ($F=2.54$, $p=0.1151$).

Clinical information regarding TBI severity as well as neuroradiological, ophthalmological, neuropsychological and subjective data for all TBI patients is represented in Table 1. In addition, the last column presents abnormal peak times (± 2 SD from control subjects) for low-level orientation (ll-o), low-level motion (ll-m), texture-segregation orientation (ts-o) and texture-segregation motion (ts-m) conditions. As there were no significant group amplitude differences between TBI and control subjects, individual differences are not represented in the table. This table permits us to assess information processing deficits of each TBI subject by using the normal limits of lIVEPs and tsVEPs, and by comparing them to the clinical information. This table shows that a direct correlation cannot always be made between clinical and functional information and that important information can be obtained:

- Many subjects (7/13) present deficits in texture segregation.
- Most of the time, when lIVEPs are affected, tsVEPs are also affected (TBI 2, 4, 9, 10, 12).
- But the reverse is not true, tsVEPs can be affected alone (TBI 1, 4: ts-m is affected but not ll-m; TBI 13: ts-o is affected but not ll-o).
- Severity does not always correlate with visual complaints and functional problems detected with VEP. For example: TBI 2 sustained a moderate TBI, had positive imaging results but normal ophthalmology, little neuropsychological deficits and no visual complaints, but did not present abnormal VEPs. Thus, even if the diagnosis and the neuroradiological results pictured an affected patient, functionally he seems close to normal. By contrast, subject number 10 is a mild TBI with normal imaging, neuropsychological deficits, visual complaints and 3 abnormal VEPs out of 4. In this case, the traditional means to evaluate dysfunctions following TBI (severity, neuroradiological results) could have underestimated the functional deficits highlighted by the VEPs.
- One could expect the VEPs to be more affected in severe TBI in comparison with mild or moderate TBI. This pattern is not always followed, in part due to TBI 6 which does not present any deficits in VEPs. This could be explained by the fact that this patient is 69 months post-trauma (recuperation process completed and some functions recovered or compensated). In fact, the recuperation process could be reflected in the number of affected VEP parameters

as seen with 4 of the 5 mild TBI subjects (TBI 3, 10, 11, 14), where the number of affected VEP measures decrease with the time-post-TBI.

- Some individual VEP abnormality patterns involving the tsVEP appear to be linked to higher-level processes implicating visual input (ex. learning and memory of complex visual material: TBI 1, 4, 10).

4. Discussion

Our findings obtained in normal and TBI subjects indicate that texture segregation typically occurs after the lIVEP (which peaks around 100 ms) and earlier than event-related cognitive potentials (which occur around 300 ms). The latter correlate with the origin of texture segregation at V1 (layers 2/3 and 5) with possible implication of associative visual areas (Lamme et al., 1992; Lamme, Van Dijk, & Spekreijse, 1993). In contrast, the lIVEP is known to have its origin strictly at V1, while event-related cognitive potentials originate from more anterior areas of the brain involving complex integrative antero-posterior cortical processes (Regan, 1989). Furthermore, the fact that the motion lIVEP yields smaller amplitudes and longer peak times than the orientation lIVEP was expected and confirms the accuracy of our stimuli, since it is known that stimuli defined by orientation produce responses of shorter peak times than those characterized by motion (Kandil & Fahle, 2003; Regan, 1989).

Our findings of increased orientation and motion-defined tsVEP peak times in TBI compared to normal controls in the presence of a normal motion lIVEP suggest altered higher-order visual processing mechanisms. It has previously been shown that more complex visual processes can be sensitive following an insult to cerebral areas involved in visual processing. For example, second-order visual processing can be impaired in the presence of spared first-order processing after a cerebro-vascular insult (Vaina & Cowey, 1996), in developmental pathologies such as autism (Bertone, Mottron, Jelenic, & Faubert, 2003) and during the normal aging process (Habak & Faubert, 2000). Furthermore, the fact that tsVEP changes can be identified in the absence of neuroradiological damage suggests that this technique can detect subtle dysfunctions in the visual pathways that are neuroradiologically 'silent'. Consequently, since post-TBI deficits in complex visuo-perceptual integration are strongly correlated with functional outcome, such a tool (tsVEP) could contribute to identify markers of cerebral recovery and have significant prognostic value (Marion, 1998; Walsh, 1985).

Since the VEP associated with texture segregation reflects visual information processing which is rather integrative than parallel, it represents a sensitive tool to study visual processing efficiency at more complex levels.

Table 1
Clinical information of TBI patients

	Severity/time post-TBI (months)	CT-scan or MRI	Ophthalmology	Neuropsychological deficits	Visual complaints (transient in nature)	Peak time			
						ll-o	ll-m	ts-o	ts-m
TBI 1 M	Severe 8	R fronto-temporal contusions	Normal	Speed of processing, attention, inhibition, executive functions, visual memory	Blurred vision, photophobia	A			A
TBI 2 F	Moderate 7	Small bleed, lateral ventricles	Normal	Concentration, planning, anxiety	None				
TBI 3 M	Mild 3	Small R parietal bleed and multiple contusions (MRI)	Normal	Verbal memory, verbal initiation, mental flexibility	None	A		A	
TBI 4 M	Severe 9	Subdural fronto-parietal hematoma	R Homonym hemianopsia	Attention, inhibition, verbal and visual learning, language comprehension, executive functions, irritability	Blurred vision	A		A	A
TBI 5 M	Mild 2	N	Normal	Speed of processing, verbal working memory, verbal learning, inhibition	Blurred vision, photophobia, diplopia				
TBI 6 M	Severe 69	R fronto-parietal and L parieto-temporal bleeds	Normal	Verbal working memory, planning, organization, visuo-spatial synthesis	None				
TBI 7 M	Moderate 13	R fronto-temporo-parietal hemorrhage	↓Near vision	Attention, verbal working memory and learning, verbal memory, mental flexibility, inhibition, irritability	Photophobia				
TBI 8 M	Moderate 4	L fronto-temporal hematoma	Normal	Unavailable	Blurred vision	A		A	
TBI 9 M	Moderate 6	Small left frontal hemorrhage	Diplopia, reduction of visual field	Speed of processing, anxiety	Blurred vision, diplopia		A		
TBI 10 F	Mild 2	N	Normal	Speed of processing, attention, concentration, organization, verbal and visual memory	Blurred vision, photophobia, diplopia	A	A	A	
TBI 11 F	Mild 5	N	Normal	Attention, concentration	Blurred vision, photophobia				
TBI 12 M	Moderate 5	L sub-arachnoid hemorrhage	Normal	Verbal working memory and learning, verbal memory, irritability, anxiety	Blurred vision	A		A	
TBI 13 F	Mild 5	R occipital hematoma (MRI)	Normal	Speed of processing, concentration, verbal memory, inhibition, irritability, anxiety	Blurred vision				A

R=right; L=left; A=abnormal= ± 2 SD from controls.

It could also be used to infer on global information processing integrity in the brain, particularly in the presence of developmental or acquired cerebral insults which are diffuse in nature and which often affect visual processing because of the localization and organization of the visual pathways in the brain (i.e. perinatal brain hemorrhage due to prematurity, traumatic brain injury, etc.). Further studies are needed to investigate in more detail the relationship between tsVEP findings and the specific nature of brain damage (i.e. diffuse vs focal, lesion site) as well as its severity (a comparison which was not done in the present study due to the insufficient number of subjects in each severity category), and in larger groups of subjects. For example, positive correlations between specific brain lesions in visual areas or diffuse brain damage and tsVEP changes could yield useful information as to the respectful impacts of such lesion patterns on visual integration or more global information processing.

In conclusion, our results show that the tsVEP, presumably higher up in the visual processing chain than the lVEP, is sensitive to TBI and thus can reveal further information as to the nature of possible information processing deficits after TBI. It could also help to quantify cortical damage that is not revealed with traditional clinical tools. Our findings strongly suggest that addition of the tsVEP as part of a clinical electrophysiological evaluation provides valuable information. It can permit an objective and rapid assessment of the quality of more complex information processing which could be affected in the absence of primary visual processing problems in certain pathologies, particularly those involving diffuse cerebral lesions. Further studies (ex. longitudinal) are also needed to determine the sensitivity/robustness of the tsVEP as well as its clinical limitations. Correlational studies with other electrophysiological (i.e. lVEP, cognitive evoked potentials) and neuropsychological (i.e. visuo-perceptual and visuo-spatial) parameters will help to objectify resulting functional impacts of TBI and determine early prognosis, which could contribute to more specific and efficient rehabilitation interventions.

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