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First- and second-order contrast sensitivity functions reveal disrupted visual processing following mild traumatic brain injury

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ABSTRACT

Vision is disrupted by traumatic brain injury (TBI), with vision-related complaints being amongst the most common in this population. Based on the neural responses of early visual cortical areas, injury to the visual cortex would be predicted to affect both 1st order and 2nd order contrast sensitivity functions (CSFs)—the height and/or the cut-off of the CSF are expected to be affected by TBI. Previous studies have reported disruptions only in 2nd order contrast sensitivity, but using a narrow range of parameters and divergent methodologies—no study has characterized the effect of TBI on the full CSF for both 1st and 2nd order stimuli. Such information is needed to properly understand the effect of TBI on contrast perception, which underlies all visual processing. Using a unified framework based on the *quick* contrast sensitivity function, we measured full CSFs for static and dynamic 1st and 2nd order stimuli. Our results provide a unique dataset showing alterations in sensitivity for both 1st and 2nd order visual stimuli. In particular, we show that TBI patients have increased sensitivity for 1st order motion stimuli and decreased sensitivity to orientation-defined and contrast-defined 2nd order stimuli. In addition, our data suggest that TBI patients' sensitivity for both 1st order stimuli and 2nd order contrast-defined stimuli is shifted towards higher spatial frequencies.

1. Introduction

Traumatic brain injury (TBI) is one of the most common causes for disability amongst the North American population affecting approximately 3.2–5.3 million people (Coronado et al., 2011; Corrigan, Selassie, & Orman, 2010). Some of the most common complaints after TBI are visual deficits (Greenwald, Kapoor, & Singh, 2012; Kapoor & Ciuffreda, 2002). Clinically, these complaints include image blur, problems with reading, double vision, motion sensitivity, and light sensitivity (for a comprehensive review see (Kapoor & Ciuffreda, 2002)). The fact that many visual symptoms persist despite normal ocular function suggests that post-chiasmic visual processing involving the thalamus or the occipital cortex may be affected. The prevalence of visual complaints in a subset of TBI patients may be indicative of more general disruption of vision—patients who are unaware of symptoms may nonetheless suffer from sub-clinical disruptions to visual performance.

While total loss of the primary visual cortex (V1) results in effective blindness (blindsight) (Cowey, 2010; Stoerig & Cowey, 1997), injury to the rest of the visual cortex results in contrast sensitivity loss for both 1st and 2nd order stimuli—stimuli that vary in a dimension other than luminance such as texture, motion and contrast, thought to involve extra-striate cortical regions (El-Shamayleh & Movshon, 2011; Larsson, Heeger, & Landy, 2010; Merigan, 2000). First-order or luminance modulation losses are smaller in magnitude than the 2nd order losses, suggesting that the extra-striate cortex may be specifically involved (Hayes & Merigan, 2006; Merigan, Nealey, & Maunsell, 1993; Schiller, 1993). For example, a lesion to the macaque visual area V2 resulted in a mild 1st order contrast sensitivity loss within the lesioned cortical region whereas perception of orientation-defined 2nd order stimuli was severely impaired (Merigan et al., 1993). Chemical lesions to macaque monkey V4 resulted in deficits in both 1st order contrast sensitivity and 2nd order contour discrimination and these findings were in notable agreement with human data from stroke patients with lesions in corresponding cortical area

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(Hayes & Merigan, 2006). Thus, the processing of 1st and 2nd order stimuli (non-luminance modulation) can be affected in TBI, suggesting that the putative diffuse injury involves both extra-striate as well as striate processing.

Describing a deficit in terms of 1st and 2nd order processing is challenging for two reasons. For example, contrast perception for 1st order stimuli might be affected by whether the stimulus is static or moving. Second-order stimuli can be defined in a number of ways, e.g., being defined solely by contrast variation, texture variation, or dynamic variations over space. Independent of the stimulus type, it is imperative that a range of stimulus parameters be tested so as to not obtain biased estimates of group differences—for instance, TBI and normal subjects may have a difference in performance at only high or only medium spatial frequencies. This information is important to identify the affected mechanisms as well as the potential means of treatment. Critically, 2nd order stimuli all have equi-detectable carriers (i.e. all carriers were set to a contrast factor above threshold). We do this to ensure that any 2nd order loss in sensitivity is not simply a consequence of a less detectable carrier (i.e. a first order loss).

Previous findings with fixed stimulus parameters suggest that sensitivity, particularly for 2nd order contrast modulated stimuli, can be affected by TBI. While sensitivity to a 1st order low spatial frequency luminance grating was not affected, sensitivity to both static and dynamic contrast-defined 2nd order stimuli at the same spatial frequency was lower in children who suffered a mild TBI (Brosseau-Lachaine, Gagnon, Forget, & Faubert, 2008). Another study showed that reaction times on a motion direction discrimination task were longer in mild TBI participants for both 1st and 2nd order stimuli using parameters comparable to a previous study. However, unlike in the control group, the reaction times for 2nd order stimuli were longer compared to 1st order stimuli in the TBI group (Piponnier et al., 2015).

Electrophysiological results appear to corroborate the psychophysical findings. Lachapelle, Ouimet, Bach, Ptito, and McKerral (2004) recorded visual evoked potentials (VEPs) to 1st and 2nd order visual stimuli and assessed the delays as well as the amplitudes of the low- and high-level VEP components. While the amplitudes did not significantly differ between the two groups in either condition—albeit on average being diminished in the TBI group—the delay was significantly longer for motion- and texture-defined 2nd order stimuli. A later study by the same group showed a prolonged event-related potential latency to motion-defined texture (2nd order) but not simple (1st order) motion or pattern reversal (Lachapelle, Bolduc-Teasdale, Ptito, & McKerral, 2008).

A particular challenge in interpreting previous findings is that the spatial frequencies tested are often limited, for example some studies used only low spatial frequency (0.5 cpd) for both 1st and 2nd order stimuli (Brosseau-Lachaine et al., 2008; Piponnier et al., 2015). In addition, the carriers contrast of the 2nd order stimuli were fixed at a constant contrast (usually 50% or 100%) and were not scaled by the 1st order sensitivity of each participant (Brosseau-Lachaine et al., 2008; Lachapelle et al., 2008; Piponnier et al., 2015). We have addressed these issues by estimating the full contrast sensitivity function (CSF) for both static and dynamic 1st and 2nd order stimuli. Our approach—utilizing the *quick* contrast sensitivity method (qCSF; (Lesmes, Lu, Baek, & Albright, 2010; Reynaud, Tang, Zhou, & Hess, 2014))—allowed us to match the 2nd order stimulus presentation parameters to their 1st order detectability across the spatial frequency range, allowing us to accurately measure alterations in 2nd order contrast perception that are independent of any 1st order performance deficit. We also measured the 2nd order sensitivity for three fundamentally different types of stimuli—stimuli defined by contrast, orientation, or motion. Using this unified approach, we observed changes to both 1st order and 2nd order visual perception, with particular differences relating to dynamic vs. static stimuli.

2. Methods

2.1. Participants

A group of 26 mild TBI participants (17 females, 9 males, mean age 34.69 years ± 14.7 SD) was recruited either from the McGill University Health Center Out-Patient TBI Program or via public advertisements. The criteria of mild TBI were as follows: (1) any amnesia of events immediately before or after the accident lasting no longer than 24 h and (2) a Glasgow Coma Score ranging between 13 and 15. If loss of consciousness was present, it had to be shorter than 30 min. Mild TBI could be sub-classified as trivial, simple or complex (presence of a positive acute intracerebral bleeding in CT scan). The time between the TBI and the testing session varied between 35 days and 96 months. All participants had normal or corrected-to-normal visual acuity and wore their habitual refractive correction during the experiment. All procedures were in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) and were approved by the Research Ethics Board of the McGill University Health Centre. Informed consent was obtained from all participants prior to data collection. A short verbal screening for relevant medical history e.g. visual and psychiatric disorders, recurrent migraines, or vertigo was administered prior to participation. The exclusion criteria were: general anesthesia within the past six months, other acquired brain injuries in the past, severe tremors, and/or epilepsy. All participants successfully completed a quick neuropsychological screening of visual attention—the Trail Making Test A (Giovagnoli et al., 1996), the Bells Test (Gauthier, Dehaut, & Joanette, 1989)—and spatial neglect—the Clock-drawing test (Ishiai, Sugishita, Ichikawa, Gono, & Watabiki, 1993) (see Table 1).

2.2. Subjective visual complaints

In order to evaluate how the TBI affected vision of our group of participants we used a modified version of the questionnaire included in the Defense Centers of Excellence guidelines for assessment of visual dysfunction associated with mTBI (Defense Centers of Excellence for Psychological Health & Traumatic Brain Injury, 2013). The questionnaire is included in Table 2. In brief, the questionnaire probes for common complaints after concussion, including blurred vision, reading difficulties, discomfort during use of computer screens, etc. Twenty two participants completed the questionnaire, and were asked to rank their responses on a scale from 1 to 10 where 1 = "not at all" and 10 = "totally". There were 11 ranked questions therefore the minimum total score was 11 and the maximum total score was 110.

2.3. Stimuli and experimental procedure

The stimulus generation procedures have been previously described in detail (Gao et al., 2014; Reynaud et al., 2014). The 1st order orientation-defined stimuli were created by filtering a white noise with horizontally- or vertically-oriented Gabor filters with a half-response spatial frequency bandwidth of 1.84 octaves, resulting in horizontally- or vertically-oriented patterns (Fig. 1B). The motion-defined stimuli were created by filtering the white noise by both orthogonal filters and were drifted either along the horizontal or vertical directions at a temporal frequency of 2 Hz. The 2nd order stimuli are best described in terms of a carrier (high-frequency texture) and an envelope (lower-frequency constraint on the carrier contrast variations over space). Thus, the