Mild traumatic brain injury induces prolonged visual processing deficits in children

ODILE BROSSEAU-LACHAINE\textsuperscript{1,2}, ISABELLE GAGNON\textsuperscript{3,4}, ROBERT FORGET\textsuperscript{2,5}, & JOCelyn FAUBERT\textsuperscript{1,2}

\textsuperscript{1}\textsuperscript{1}École d'optométrie, Université de Montréal, Montréal, Québec, Canada, \textsuperscript{2}Centre de recherche interdisciplinaire en réadaptation du Montréal Métropolitain (CRIR), Montréal, Québec, Canada, \textsuperscript{3}Trauma Programs, Montreal Children’s Hospital, McGill University Health Center, Montréal, Québec, Canada, \textsuperscript{4}School of Physical and Occupational Therapy, McGill University, Montréal, Québec, Canada, and \textsuperscript{5}École de réadaptation, Faculté de Médecine, Université de Montréal, Québec, Canada

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Abstract

Primary objective: To compare the sensitivity to simple and complex visual stimuli of children who have sustained a mild traumatic brain injury (mTBI) to that of matched non-injured children and to determine the evolution of visuo-perceptual performance over time.

Research design: A prospective design was used to assess 18 children with mTBI and 18 matched healthy controls (8–16 years of age).

Methods and procedures: Sensitivity to static and dynamic forms of simple (first-order) and complex (second-order) stimuli were assessed at 1, 4 and 12 weeks post-injury and at equivalent times for controls. Orientation and direction identification thresholds were measured for all participants for static and dynamic conditions, respectively. In addition, sensitivity to radial optic flow (inward vs outward), a complex motion stimulus, was assessed.

Main outcomes and results: Thresholds measured from all complex stimuli were significantly affected for the mTBI children over time whereas no difference in threshold between groups across all testing conditions was found for simple, first-order information. Sensitivity to all complex stimuli was still affected 12 weeks after the injury.

Conclusion: These findings suggest that injured children present selective processing deficits for higher-order information and that this deficit persists over relatively long periods. Such measures could be useful to assess children who have sustained mTBI and possibly contribute to identifying potential risks of returning these children to demanding physical activities.

Keywords: Visual perception, sensory integration, mild traumatic brain injury, paediatrics, second-order, optic flow

Introduction

A large portion of the human brain is involved in vision and given the vulnerability of cerebellar and cortical tracts to shearing injury, a variety of visual impairments have been reported following a traumatic brain injury (TBI) \cite{1–6}. The identified deficits are usually focused on oculomotor disorders, loss of acuity; loss of visual field; loss of binocularity; cranial nerve palsies with extra-ocular motility, and few authors have investigated the perception of visual stimuli or the integration of visual information for use in functional activities after TBI.

The perception of visual stimuli is generally achieved through the attributes of the stimuli themselves. When objects are defined by attributes such as luminance and colour, they are said to...
possess ‘first order’ (i.e. simple, linear) properties. On the other hand, when objects can only be perceived by their contrast, texture or depth, they are said to have ‘second order’ (i.e. complex, non-linear) properties and additional information processing is required to perceive the image [7, 8]. Psychophysical and physiological evidence, along with computational modelling, suggest that two separate cortical mechanisms underlie the initial processing of first- and second-order stimuli, where an additional processing step is needed for second-order stimuli [9–12].

There is little documentation of the specific impact of mild TBI (mTBI) on the visual system and particularly on the individual’s ability to perceive and integrate complex visual information. Indeed, studies investigating the consequences of mTBI have mostly concentrated on investigating cognitive functioning and generally report impaired information processing speed, working memory, attention, memory and executive functions [13–15]. More recently, balance deficits have been documented in mTBI children [16] and adults [17–21]. Examining the consequences of even a mild brain injury on visual perception and processing is important because in order to behave and navigate through the environment in an efficient and adaptive manner, one must first construct a visual representation of one’s surroundings. To achieve this, one’s visual brain must integrate local information across time and space into a coherent visual percept.

Work conducted by this group [22, 23], investigated visuo-motor performances of children with MTBI and demonstrated that the injured children manifested response-time deficits under certain experimental conditions involving complex visuo-motor tasks (i.e. catching a moving stimulus), but no deficits in reaction and movement time for classical simple or choice response time paradigms. Although these studies were primarily aimed at identifying response-time deficits, the question of whether perceptual deficits of the visual system could be responsible for those slower response times was raised and it was questioned if the nature of the visual stimulus itself (i.e. complex) could have contributed to the difference in visuo-motor performance of children with and without mTBI. Others used visual evoked potential (VEP) to investigate similar concepts in adults and have demonstrated that higher-level VEPs (e.g. texture segregation, cognitive EPs), which permitted the detection of subtle deficits which remained indistinguishable with standard electrophysiology or neuroimaging [24, 25] were sensitive to mild-to-moderate TBI and suggested possible resulting visual information processing deficits after the injury. To the authors’ knowledge, no study has investigated the perception of complex visual stimuli in children who suffered a mTBI.

One way to investigate the capacity of individuals to visually integrate information is to use simple orientation- and direction-identification paradigms for static and moving stimuli, respectively. One such paradigm uses first- and second-order visual stimuli that differ in the amount of neural integration needed to perceive its direction or orientation; probing either early- or later-level visual cortical function [7, 9, 26, 27]. Measurements of the sensitivity to first- and second-order motion have been demonstrated to be very sensitive to subtle neural deficits in different populations such as non-pathological ageing [8], high-functioning autism [28, 29] and fragile X syndrome [30]

Another type of dynamic and complex visual information is referred to as optic flow motion. Optic flow is a type of complex motion information that has great ecological validity, since it exemplifies the visual pattern perceived as one navigates through one’s environment [31]. Gibson [32] proposed that the direction of self-motion (as in locomotion) can be directly perceived from the ‘focus of radial outflow’ in the optical flow pattern. One paradigm to test optic flow is the presentation of radial motion stimuli (e.g. randomly generated white dots on a black background) that travel towards (expanding field) or away from (contracting field) the observer. At least one group has used the assessment of such concepts in adults with mTBI found destabilizing effects of visual field motion (virtually moving the room in different directions) for the duration of a follow-up study which lasted up to 30 days post-injury [33]. The assessment of the perception of optic flow information in children with mTBI can therefore give important insight on their ability to integrate and efficiently perceive their environment as they navigate through it.

The present study assessed the perception of simple and complex visual stimuli after a mTBI in children, in the acute phase. The objectives were to (1) determine whether children who have sustained a mTBI presented a decreased sensitivity for complex visual stimuli when compared to matched non-injured children and (2) explore the evolution of the visual perceptual performance of children with and without mTBI during the first 3 months following the injury in children with mTBI.

Methods

Participants

Eighteen children having sustained a mTBI and an equivalent number of children without any history of brain injury accepted to participate in this study.
All participants were aged between 8–16 years. Children from the mTBI group were recruited from consecutive hospital admissions to the Trauma and Injury Prevention Program from the Montreal Children’s Hospital (McGill University Health Center, Montreal, Canada) and to the Emergency Department of Sainte-Justine Hospital (Montreal University Hospital Center, Montreal, Canada). All injured participants were considered normal on a standard neurological examination done prior to discharge from the hospital. The inclusion criterion for the injured group was a diagnosis of mild TBI made by the professionals of the recruiting hospitals, as defined by the American Congress of Rehabilitation Medicine [34] and the WHO Collaborating Centre for Neurotrauma Task Force on mTBI [35]. This includes at least one of the following criteria after an acute brain injury resulting from mechanical energy to the head: confusion or disorientation, loss of consciousness for 30 minutes or less, any loss of memory for events immediately before or after the accident lasting less than 24 hours and/or other transient neurological abnormalities not requiring surgery. Also, a Glasgow Coma Scale (GCS) score of 13–15 within 30 minutes of the injury [34, 35]. Participants received a complete eye exam by an optometrist and had to have normal or corrected-to-normal vision (acuity of 6/6 or better), a normal ocular health (pupillary reflexes, ocular motilities, biomicroscopy and fundus) and binocular vision (excluding heterophoria and tropia, normal stereoscopic vision). All participants had typical academic backgrounds (i.e. they attended age-appropriate classes, according to standard school schedules in Quebec) and development. They were screened to exclude pre-morbid diagnosis of learning disabilities, attention deficits and hyperactivity disorder as well as regular use of psychostimulant drugs and/or behaviour problems. Children for the comparison group were recruited among friends of children with mTBI when possible or from the community. The groups were matched as closely as possible in terms of gender and chronological age. They had no history of any form of head injury. The mean chronological age of the children included in the mTBI and control groups were 12.56 (SD 2.38) and 12.44 (SD 2.37), respectively (for children aged between 8–16 years).

Table I presents the characteristics of the brain injury sustained by this sample (mTBI group). Reported injuries were from accidental impacts to the head (hits and/or falls) and during recreational activities, such as bicycling, playing hockey, basketball, soccer, football or skiing. The majority of the sample had a GCS score of 15 at the admission to the hospital (average of 14.72). Eighty-three per cent of children had sustained mTBI that could be categorized as ‘simple concussion’, while 17% had sustained ‘complex’ concussions, according to this recently introduced typology [36]. An informed written consent was obtained from all participants and their legal guardians, prior to data collection. The ethics and scientific committees from the Institutional Review boards of the Montreal Children’s Hospital of the McGill University Health Centre and of Sainte-Justine Hospital approved the study.

**Table I. Participants characteristics for mTBI group.**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Frequency</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gender</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boys</td>
<td>10</td>
<td>56</td>
</tr>
<tr>
<td>Girls</td>
<td>8</td>
<td>44</td>
</tr>
<tr>
<td><strong>Cause of injury</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Falls</td>
<td>9</td>
<td>50</td>
</tr>
<tr>
<td>Bicycle falls</td>
<td>4</td>
<td>22</td>
</tr>
<tr>
<td>MVA, bicycle</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Hits (hockey, ball, etc)</td>
<td>4</td>
<td>22</td>
</tr>
<tr>
<td><strong>Admission GCS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>5</td>
<td>28</td>
</tr>
<tr>
<td>15</td>
<td>13</td>
<td>72</td>
</tr>
<tr>
<td><strong>Duration of LOC</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No LOC</td>
<td>11</td>
<td>61</td>
</tr>
<tr>
<td>0–1 min</td>
<td>6</td>
<td>33</td>
</tr>
<tr>
<td>&gt;1 min</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td><strong>Duration of PTA</strong></td>
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<td></td>
</tr>
<tr>
<td>0–60 min</td>
<td>15</td>
<td>83</td>
</tr>
<tr>
<td>&gt;60 min</td>
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<td>83</td>
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<tr>
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<tr>
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<tr>
<td>Nausea–Vomiting</td>
<td>8</td>
<td>44</td>
</tr>
<tr>
<td>Dizziness</td>
<td>8</td>
<td>44</td>
</tr>
<tr>
<td>Drowsiness</td>
<td>8</td>
<td>44</td>
</tr>
<tr>
<td>Visual Problems</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>Altered gait</td>
<td>2</td>
<td>11</td>
</tr>
</tbody>
</table>

GCS: Glasgow Coma Scale; LOC: loss of consciousness; MVA: motor vehicle accident; PTA: post-traumatic amnesia.

**Apparatus**

The stimuli were presented and the data were collected by a Power Macintosh G3 computer. Presentation was done on a 16-inch Apple monitor for first- and second-order stimuli with a frame refresh rate of 75 Hz and a screen resolution of 1024 x 768 pixels. For optic flow stimuli, stimuli were rear-projected (InFocus LCD projector, LP725) on a large light diffusing tangent screen (Da-lite; 1.06 × 0.8 m) with a frame refresh rate of 60 Hz and a screen resolution of 800 x 600 pixels. Stimulus generation and animation was controlled by the VPixx© graphics program, version 1.88.
Participants underwent psychophysical testing to determine their visuo-perceptual thresholds for static and dynamic first- and second-order stimuli and radial optic flow stimuli using two-alternative forced choice (2-AFC) orientation or direction discrimination.

Static conditions. Figure 1 represents a schematic of the first- and second-order stimuli that were used to assess perceptual performances in children after a mTBI.

The static conditions required participants to identify the orientation of horizontal or vertical gratings, presented as first- or second-order patterns. Each stimulus was within a hard-edged circular region at the centre of the display, subtending 10° in diameter at a viewing distance of 57 cm. The mean luminance of the display was 30.5 cd m$$^{-2}$$ ($$u' = 0.1918$$, $$v' = 0.4344$$ in CIE [Commission Internationale de l’Eclairage] $$u'$$ $$v'$$ colour space) where $$L_{\text{min}}$$ was 0.5 and $$L_{\text{max}}$$ was 60.5 cd m$$^{-2}$$. First-order stimuli were a simple type of stimuli that were luminance-defined (luminance-modulation depth) and were constructed by adding static grayscale noise to the modulating sine wave grating. While second-order stimuli, a complex type of stimulus, were texture-defined (contrast-modulation depth) and produced by multiplying rather than adding the static grayscale noise to the modulating sine wave grating, the noise dots’ individual luminances were randomly assigned as a function of sin (x), where (x) ranged from 0–2 $$\pi$$. The average contrast of the noise was set at half its maximum value. All stimuli had a spatial frequency of 0.5 cycle per degree (cpd).

The orientation-identification thresholds for the first-order stimuli were found by varying the contrast, i.e. the luminance modulation depth, defined as the amplitude of the modulating sine wave, which ranged between 0.0–0.5:

$$\text{Luminance modulation depth} = \frac{L_{\text{max}} - L_{\text{min}}}{L_{\text{max}} + L_{\text{min}}}$$

where $$L_{\text{max}}$$ and $$L_{\text{min}}$$ refer to the average highest and lowest local luminances in the stimulus. These first-order patterns were presented at five-to-six levels of luminance modulation along log steps (0.04, 0.02, 0.01, 0.005, 0.0025 and 0.00125).

Thresholds for second-order stimuli were found by varying the contrast-modulation depth of the static pattern, defined as the amplitude of the modulating sine wave, which ranged between 0.0–1.0:

$$\text{Contrast modulation depth} = \frac{C_{\text{max}} - C_{\text{min}}}{C_{\text{max}} + C_{\text{min}}}$$

where $$C_{\text{max}}$$ and $$C_{\text{min}}$$ are the maximum and minimum local contrasts in the pattern. This type of stimulus was also presented at five-to-six pre-determined levels of contrast modulation (0.5, 0.25, 0.125, 0.0625, 0.0314 and 0.0156).

Dynamic conditions. The stimuli used for the direction-identification task in the dynamic condition are illustrated in Figure 1(b). Except for their dynamic characteristic, the moving stimuli used for the direction-identification task were identical with the static stimuli previously described for the orientation-identification task in terms of physical properties and parameters. The vertically-oriented gratings were moving either to the right or to the left, with a drift frequency of 2 Hz. First- and second-order dynamic patterns were also constructed by adding or multiplying static grayscale noise to the modulating sine wave grating. The dynamic first-order patterns were presented at five-to-six levels of luminance modulation (0.02, 0.01, 0.005, 0.0025, 0.00125 and 0.000625). For the dynamic second-order patterns, the same levels of contrast modulation were presented as for static second-order stimuli.

Optic flow stimuli. Radial optic flow stimuli used in this study simulate an observer moving in
translation through a circular tunnel [37]. A fixation point appeared first for 1 second in the centre of the screen (red dot subtending 0.5°). Then, a radial outward or inward moving pattern appeared for 1 second. The pattern was constructed with 150 moving white dots (10 cd m\(^{-2}\); 0.52 × 0.52° of visual angle), randomly distributed (with uniform density) on a dark background (1.8 cd m\(^{-2}\); for a Michelson contrast of 70%; \(\mu' = 0.1815\) and \(\psi = 0.5053\)) of large extent, subtending 104° × 79° of visual angle. In order to simulate the optic flow motion seen in the environment, the elements follow a radial trajectory from the centre of the pattern. In addition, dot speed was projection-specified, meaning dot acceleration increased as dots moved into the periphery. This acceleration was calculated using the square of the distance from the origin of expansion, i.e. by a factor of four as the distance doubled. Specifically, the dot speed was 7.5 s\(^{-1}\) at 10° and would travel at a speed of 30 s\(^{-1}\) at 20° of eccentricity. The dots were following their trajectory in a continuous manner, with no limited lifetime. Different levels or proportion of dot coherence were presented. For example, for a coherence level of 50%, half of the dots were moving in the same direction and the other half were moving with the same speed but in random direction in the same path (jittering). This stimulus was presented at five-to-six levels along log steps starting at 100% of coherence, to seek a minimum proportion of dots moving in the same direction that yields a coherent percept. This stimulus is also qualified as ‘complex’ because of the larger neural integration required for perceiving the overall direction of the optic flow motion.

**Other measures.** To ensure that participants had normal visual fields, they underwent the Frequency Doubling Technology (FDT; Humphrey Viewfinder™ Systems) perimetry assessment at each testing session. The C-20 full threshold mode test was used for both eyes independently. In the central 20° of the visual field, a central location was tested and four locations were tested in each quadrant. Thresholds in dB were obtained for every location, using a series of black and white bands varying in contrast that flicker at 25 Hz.

Moreover, a questionnaire, based on the Rivermead Post-Concussion Symptoms (PCS) was administered to both groups at every testing session [38]. Information about the trauma was extracted from the child’s medical record in order to describe the characteristics of the brain injury sustained (see Table I).

**Testing procedures**

Participants were tested during three separate sessions at three pre-determined times following recruitment to the study, which was after \(~1\) week (mean ± SD of 4.5 days ±1.72 after recruitment and 7.72 days ±2.72 post-injury); 4 weeks (mean of 4.19 weeks ±0.54 after recruitment) and 12 weeks (mean of 12.47 weeks ±0.99 after recruitment) and at corresponding time intervals for controls. These time sessions were chosen because of their importance in the child’s recovery. The initial assessment was to seek a measure in the acute phase, the 4th week corresponds to the end of an activity restriction period imposed on children having sustained the most severe mTBI [39] and the 12th week was chosen because most post-concussion reported symptoms are generally resolved by that time [40]. One child from the mTBI group could not complete the first evaluation because of the severity of his symptoms (headaches), but did complete the two subsequent assessments. In addition, two other mTBI children did not complete the study after the first and the second evaluation, for personal reasons.

The testing sessions took place at the Visual Psychophysics and Perception Laboratory located in School of Optometry of Université de Montréal. If a recent eye exam on the child was not available, a complete optometric assessment was done and child’s vision was corrected to normal when necessary. Each session lasted \(~75\) minutes (without the optometric examination). The children were tested in a dimly lit room, sitting in a comfortable chair, at a distance of 57 cm from the screen upon which each visual stimulus was presented. The viewing of the display was binocular and the children fixated a red dot centred on the screen. Each psychophysical session was of five testing conditions (i.e. static and dynamic conditions for first and second-order stimuli and optic flow) where the order was counterbalanced across appointments and participants. Instructions were given verbally before each test and practice trials with feedback were completed to familiarize participants with every task.

For both first- and second-order static conditions, the children were required to identify the orientation of horizontally or vertically presented lines after each presentation. In the dynamic conditions, participants had to identify the motion direction of first- and second-order patterns that were moving either rightward or leftward. Each stimulus was presented for 1 second, after which the child gave the experimenter an appropriate verbal or non-verbal (i.e. a hand gesture) response, depending on the experimental condition (2-AFC). The experimenter initiated each trial only when the participant
attended to the screen and entered each response obtained from the observer. The same general procedure was used for the optic flow stimuli. The children were required to discriminate whether the flow field was expanding (moving away from the centre on the screen giving sensation of motion towards the subject) or contracting (towards the centre on the screen or giving the impression of motion away from the subject), after each presentation.

A method of constant stimuli was used to measure thresholds for all conditions. The pre-determined modulation depth (for first- and second-order patterns) or coherence levels (for optic flow) were randomly varied in each experimental condition. Stimuli were presented 10 times for either orientation or direction, for a total of 20 trials for each modulation depth or coherence level for every testing condition. Weibull [41] functions were fitted to the obtained responses in order to estimate orientation- or direction-identification thresholds at a 75% correct level of performance (bootstrap program; Matlab v. 6.5).

Data analysis

Thresholds were measured for each child in each of the following conditions: orientation-identification thresholds for first- and second-order static information, direction-identification thresholds for first- and second-order dynamic information and direction discrimination for optic flow stimuli. Log-transform data of these thresholds were used in the statistical analysis. Also, threshold of central location from the FDT and scores on post-concussion symptoms questionnaires were computed.

Analyses of variance were performed to investigate the differences within each condition and test performances of the children in the mTBI group compared with the control group. A two-way (group and time) mixed model ANOVAs with repeated measures on the time factor was used. Post-hoc independent t-tests with Bonferroni correction were used to determine differences between groups at each assessment time. One-way ANOVAs with repeated measures were also used to assess the specific time effect for each group, when needed. The ANOVAs were done only on complete data sets. However, bar graphs and t-tests were done using all available data. Relations between mTBI group’s post-concussion symptoms and performance on relevant measures, such as contrast modulation depth thresholds, were analysed with Pearson correlation. Statistical analyses were carried out with the SPSS statistical package (version 13; SPSS Inc.)

Results

Static conditions

Figure 2 shows the mean orientation-identification thresholds for mTBI and control groups for first-order (Figure 2a) and second-order stimuli (Figure 2b) as a function of experimental sessions in time. Separate analyses were performed for the two types of stimuli, because of their qualitatively different defining attributes making a direct comparison non-informative. The two-way ANOVA performed on the log transform orientation-identification thresholds for first-order static stimuli (luminance modulation depth thresholds) revealed no statistically significant group-by-time interaction ($F(2,62) = 2.515, p = 0.089$), neither as significant differences between groups across all testing sessions ($F(1,31) = 0.133, p = 0.717$) or on the time factor (repeated measures) ($F(2,62) = 2.162, p = 0.124$).

Figure 2. Static conditions. Mean orientation-identification thresholds (+1 SEM) for mild traumatic brain injury (mTBI) (open bars) and control children (filled bars) for first-order (a) and second-order (b) stimuli at 1, 4 and 12 weeks. (a) First-order static stimuli. No difference in thresholds was found between groups across all testing sessions either on the time factor. (b) Second-order static stimuli. A significant between-group effect was found but no main effect on the time factor, neither as for group × time interaction. Insets show a schematic of the conditions tested.
The mixed within-between ANOVA conducted on orientation-identification thresholds for second-order stimuli (contrast modulation depth thresholds) did neither reveal an interaction effect of group membership and time ($F(2,60) = 0.411, p = 0.665$), nor a main effect of time ($F(2,60) = 1.80, p = 0.174$). The analysis did, however, reveal a statistically significant difference between groups ($F(1,30) = 4.186, p = 0.05$), indicating higher thresholds for the mTBI group as compared to the control group. Specifically, post-hoc analysis revealed that injured children's thresholds were significantly higher than those of the non-injured at 4 weeks only ($t = 2.56, p = 0.015$, with Bonferroni correction). The absence of significant effect on the time factor for both type of stimuli (first- and second-order) demonstrates that no learning effect was present between experimental sessions for both groups.

**Dynamic conditions**

For dynamic conditions, a similar pattern of results was found for the first- and second-order motion stimuli, as for static conditions. Luminance modulation depth thresholds from dynamic first-order stimuli did not differ significantly between mTBI and controls participants. The ANOVA demonstrated no between-group effect for this direction-identification ($F(1,30) = 0.007, p = 0.936$) and no main effect for the time factor ($F(2,60) = 0.650, p = 0.526$). Figure 3(a) demonstrates the mean thresholds obtained for both groups with these simple moving stimuli.

For the contrast modulation depth thresholds of second-order moving patterns there was a strong between-group effect (mTBI vs controls) ($F(1,30) = 13.334, p = 0.001$), as shown in Figure 3(b). There was no main effect for the time factor ($F(2,60) = 0.832, p = 0.440$) and no group by time interaction ($F(2,60) = 0.137, p = 0.872$). More specifically, higher thresholds were obtained from the mTBI group compared to the control group at week 1 ($t = 2.786, p = 0.009$), week 4 ($t = 3.012, p = 0.005$) and week 12 ($t = 2.478, p = 0.019$) (but not significant at week 12 with Bonferroni correction: $p < 0.017$).

For first-order static and dynamic conditions, the analysis showed no significant group or testing time effects. This implies that perceptual performances for simple visuo-spatial information are equal between groups and across time sessions.

In contrast, the second-order static and dynamic conditions analyses indicate that control children had significantly better performances than children who suffered from a mTBI. Moreover, the lack of significant interaction between groups and testing times shows that difference between groups are maintained across the testing period, up to 3 months post-injury.

**Optic flow condition**

Coherence thresholds were successfully obtained for all participants with the exception of one in each group (mTBI group: week 12, controls: week 1) when tested with the optic flow condition. The coherence thresholds were significantly higher for the mTBI group as compared to the control group, as revealed by the between-group effect of the performed ANOVA ($F(1,28) = 6.486, p = 0.017$) (Figure 4).

There was a main effect for the time factor (repeated measures) ($F(2,56) = 16.413, p < 0.001$), but there was no group-by-time interaction ($F(2,56) = 0.009, p = 0.991$). Post-hoc analysis...
indicated that children with mTBI performed worse, exhibiting higher thresholds as compared to children in the control group, but only at 1 week post-injury ($t = 2.605, p = 0.014$, with Bonferroni correction). The time effect was present in each group, when the groups were taken separately (for mTBI: $F(2,26) = 8.205, p = 0.002$; for controls: $F(2,30) = 8.438, p = 0.001$). Children from the mTBI group presented higher coherence thresholds to optic flow in the 1st week when compared to those of the 4th ($p < 0.001$) and of the 12th ($p = 0.028$) week. Similar to the injured children, non-injured participants improved their performance between weeks 1 and 4 ($p = 0.007$) and between weeks 1 and 12 ($p = 0.012$). This implies a learning effect between the first and the following assessments for both groups. Furthermore, the lack of a significant interaction revealed that the differences between groups were maintained throughout the assessment period after the injury and implies that there was no significant recovery across testing sessions.

Other measures

For the post-concussion symptoms, Figure 5 demonstrates the mean scores obtained for mTBI and control children from the questionnaires, as a function of experimental session in time.

Statistical analysis demonstrated a group-by-time interaction ($F(2,52) = 5.161, p = 0.009$). There was no significant group effect for all testing sessions although there was a tendency ($F(1,26) = 3.77, p = 0.063$) for mTBI participants to report more post-concussion symptoms than controls. This implies that there was initially a significant difference in the reported symptoms between the groups, with mTBI children reporting more symptoms compared to the control group (week 1 ($t = 4.464, p < 0.001$) and then a recovery in this difference (week 4: $t = 1.671, p = 0.106$; week 12: $t = 0.677, p = 0.504$)). Moreover, there was a time session effect with repeated measures ($F(2,52) = 8.425, p = 0.001$). When the groups were analysed separately, the time effect was present only for mTBI children ($F(2,20) = 7.469, p = 0.004$) and injured children improved significantly between the first and the 12th week ($p = 0.028$) only. In contrast, no time effect was present for non-injured children ($F(2,32) = 0.578, p = 0.567$).

For mTBI children, there was no significant correlation between the scores obtained on the post-concussion symptoms questionnaire and thresholds from second order static ($r = 0.353, p = 0.237$), dynamic stimuli ($r = 0.268, p = 0.376$) and optic flow patterns ($r = 0.039, p = 0.9$) at week 1. This indicates that there was no relation between the number and severity of symptoms reported after a mTBI and perceptual performances to complex stimuli indicating that this study is assessing different elements with these measures.

An additional assessment was performed to compare injured with non-injured children in terms of contrast sensitivity (FDT). Statistical analysis demonstrated that there were no significant differences in the central FDT measures, for right and left eyes separately, between the two groups or across testing sessions.
Discussion

Deficits of higher level processing after mTBI

This investigation used a prospective design to assess visuo-spatial information perception in the acute phase after a mTBI in children. The overall findings showed perceptual deficits for complex visual information despite a normal neurological examination at the time of hospital discharge. Indeed, injured children were selectively impaired on second-order, static or dynamic contrast-defined and optic flow pattern perception, compared with their non-injured controls. Furthermore, this discrepancy in perceptual performance for complex stimuli was maintained throughout the assessed period, up to 3 months post-injury. In contrast, results obtained in this study showed that sensitivities to simple visual information, more specifically static or dynamic luminance-defined stimuli, were unaffected for children who suffered a mTBI. Also, normal central contrast sensitivity (FDT) for a 25 Hz flickering stimulus was found.

These findings revealed specific impairment for mTBI children to integrate local elements in more complex visual patterns, such as second-order and optic flow stimuli. This possibly reflects a deficiency of the integrity of the occipito-parietal and occipito-temporal regions in higher level visual cortical functions, assessed with dynamic and static stimuli, respectively. The normal lower level function demonstrated with average first-order sensitivity, as opposed to the higher level function deficits, highlights a clear effect of complexity and a possible generalized deficit in cortical integrative mechanisms. This also suggests that the observed impairments did not result from a general visual impairment.

The two types of dynamic and static stimuli are physically similar, permitting a comparison of the neural integrity of the two cortical visual streams at both early and later levels. In fact, first- and second-order stimuli tap into different hierarchical levels in the visual cortex [12, 42]. First-order patterns are considered simpler because they are efficiently processed by the visual system. Specifically, local luminance variations are analysed by neural detectors in area V1 for the detection of direction or orientation. Whereas, second-order information is recognized as complex, as it requires additional non-linear neural processing to be perceived. Higher visual areas would be implicated in this processing, with recruitment of more extended neural circuitry, such as V3 and VP, and V5 for both types of dynamic stimuli [42].

Low and high levels processing in ageing and other pathologies

As reported above, other studies from the laboratory have shown a complexity effect with comparable first- and second-order visual stimuli, such as in the investigation of visual perception in ageing [8]. A larger sensitivity decrease was found for second-order stimuli in elderly, suggesting that non-pathological ageing may affect the additional processing steps required for the analysis of higher level stimuli. Moreover, the authors suggested that diffuse and non-specific cell dysfunction in ageing could account for their results. Similar to ageing, this study proposes that the elevated thresholds for higher-order stimuli in children who suffered a mTBI reveal a diffuse, generalized later-level integration malfunction rather than a region-specific impairment.

Similar to other populations where neurobiological alterations are suspected such as individuals with autism and fragile X, this group has also demonstrated impairments of the neuro-integrative mechanisms used to detect complex motion and static stimuli [28–30]. It appears, therefore, that using the first- vs second-order (simple vs complex) methodology is quite sensitive to neurobiological alterations. Other studies have shown that this approach may not only be sensitive but is also quite selective in distinguishing among populations. For instance, this study has shown that in glaucoma the second-order motion processing was not more affected than the first-order motion processing [43]. Glaucoma is an ocular disorder that affects the retinal ganglion cells of the retina that feed motion sensitive cells [44, 45] and these patients have been shown to have motion processing deficits [44–48]. As it is primarily a low-level neuropathy, it is not expected that higher-level motion processing would be more affected than the lower-level processing as supported by the results. It is clear, therefore, that when one obtains a selective reduction of second-order processing, that this represents some form of neurobiological alteration (anatomically and/or physiologically) which affects higher-level processing. An argument can be made that these techniques can be useful in the assessment of these populations.

Another interesting finding is that perception of optic flow stimuli was also affected in this group of children with mTBI. Impaired perception of optical flow has also been shown in other populations presenting cortical damage, such as patients with Alzheimer’s disease [49, 50]. This is interesting because optic flow is known to require complex visual processing because signals from a multitude of directions must be integrated to generate a coherent percept. This further supports the proposition that
the mTBI group is still not at normal levels 12 weeks post-injury. However, if one had to select a specific testing procedure between the first- and second-order grating tests or the optic flow one must favour the former approach because, while the grating task was not affected by learning, there was a clear learning effect for optic flow in both the controls and mTBI groups.

**Visual deficits and symptoms after TBI**

The investigation of visual perception *per se* after a brain injury in children has been neglected in the literature, but other work has raised the possibility that tasks requiring intact integration of various visual information could be affected following a mTBI. Indeed, a previous study had shown selectively decreased scores in preschool children who had sustained a mTBI, when tested with interpreting visual puzzles in a cognitive battery 6 months after the accident. This impairment persisted in the long-term, up to the age of 6.5 years [51]. In adults with mild-to-severe TBI, Lachapelle et al. [24] have shown abnormal visual evoked potentials (VEP) with textures segregated by gradients of both orientation and motion. In concordance with these conclusions, they have suggested altered higher-order visual processing mechanisms after TBI. Another study showed postural dysfunctions in response to visual field motion in a virtual reality environment of young adult athletes after an mTBI that was present up to 30 days post-injury. The authors suggested that trauma induced sensory integration dysfunction [17].

Children within the mTBI group reported more post-concussion symptoms to the questionnaire than did control children at the first assessment (week 1). Self-reported subjective symptoms have normalized with time, with children becoming asymptomatic, on average, at 1 and 3 months post-injury. However, results showed that even when the children became asymptomatic, their ability to process complex visual information was affected. This demonstrates that the higher-order measures were sensitive enough to detect subtle brain dysfunction even after very mild brain injuries. An interesting finding here was the lack of significant correlations between thresholds for processing complex visual information and self-reported symptoms. This would lead one to believe that these functional tests and the self-reported symptoms scales measure different consequences of brain trauma. It also raises the question as to the validity of returning mTBI children to regular activities based only on the resolution of reported symptoms.

Surprisingly, these findings demonstrated no recovery of visual processing abilities over the 12-week assessment period for children with mTBI. Indeed, the impaired sensitivity to complex visual information lasted throughout the acute phase post-injury, i.e. encompassing the first 3 months after TBI [14]. In a comparable paediatric sample, balance deficits were also reported at 12 weeks after a mild TBI [16]. While there is a debate in adult mTBI literature whether cognitive performance deficits persist beyond the initial post-injury period, some studies have reported sustained post-concussive impairments [52–55]. Furthermore, persistent neurobehavioural deficits in symptomatic sub-groups have been reported at least 12 months post-injury [56] and neuropsychological anomalies were revealed in symptomatic as well as asymptomatic concussed athletes even several weeks post-injury [57].

It is possible that this higher-order perceptual deficit could have some consequences on activities of daily living. In fact, Gagnon et al. [58] have shown, with similar mTBI children, a lack of confidence in their performance in physical activities 3 months post-injury, assessed with self-efficacy questionnaires. Possibly, the perceptual impairments revealed in this study might be expressed in demanding activities, such as team sports, thus affecting the children’s self-confidence. This could also put them at greater risk of re-injury when returning to their physical and recreational activities.

**Conclusion**

In conclusion, the present study sheds some light on visual perception skills of children who suffered a mTBI. Injured children showed normal sensitivity to visual perception of simple stimuli. In contrast, a different picture was revealed with stimuli necessitating more complex visual information processing. First, these findings demonstrate that the complex perceptual deficits persisted up to 3 months after mTBI. In further studies a longer follow-up will be useful to assess the resolution or the persistence of this perceptual deficit in time. Secondly, this study argues that the psychophysical techniques used presently represent a sensitive tool in the assessment of deficits after a mTBI in children. More specifically, it is argued that assessing first- and second-order processing represents an optimal strategy for the evaluation of the post-injury neurocognitive status. Thirdly, it is concluded that the perceptual testing measures different functions than the self-reported symptom questionnaires. Finally, such perceptual measures could significantly contribute to the clinical post-injury evaluation for preventing premature returns to activities and sports and potentially reduce risks of further injury.
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