Virtual reality as a screening tool for sports concussion in adolescents

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Abstract
Primary objective: There is controversy surrounding the cognitive effects of sports concussion. This study aimed to verify whether the technique of virtual reality could aid in the identification of attention and inhibition deficits in adolescents.
Study design: A prospective design was used to assess 25 sports-concussed and 25 non-sports-concussed adolescents enrolled in a sport and education programme.
Methods and procedures: Participants were evaluated in immersive virtual reality via ClinicaVR: Classroom-CPT and in real life via the traditional VIGIL-CPT.
Main outcomes and results: The neuropsychological assessment using virtual reality showed greater sensitivity to the subtle effects of sports concussion compared to the traditional test, which showed no difference between groups. The results also demonstrated that the sports concussion group reported more symptoms of cybersickness and more intense cybersickness than the control group.
Conclusions: Sports concussion was associated with subtle deficits in attention and inhibition. However, further studies are needed to support these results.

Keywords: Virtual reality, virtual classroom, ClinicaVR: Classroom, sports concussion, mTBI, mild traumatic brain injury, adolescents

Introduction
The term sports concussion refers to a case of mild traumatic brain injury (mTBI) resulting from a sport accident. Sports concussion is defined as change in mental status resulting from trauma or rotational forces to the brain, with or without loss of consciousness [1]. Concussions represent 8.9% of all high school athletic injuries and 5.8% of all collegiate athletic injuries and they occur in sports such as hockey and football, as well as soccer, basketball, lacrosse and wrestling [2]. According to Sosin et al.(1996) approximately 300,000 sport-related concussion occur annually in the United States [3]. Given that the direct and indirect costs of sports concussion are estimated at nearly US$17 billion [4], continued research in this area is a worthwhile endeavour.

Research on mTBI, both sports-related and non-sports-related, has been gaining prominence in the literature. Empirical research conducted in the 1980s by Bart and colleagues [5, 6] has served as the foundation for subsequent studies. While certain people experience at least some of the cognitive effects of mTBI for the rest of their lives, others...
recover from it; the nature and the duration of the post-acute recovery process are still a matter of debate [7]. While most people with non-sports-related mTBI tend to show strong recovery over the 3 months after their accident [8–14], some experience persistent symptoms beyond this period. The prevalence of post-acute symptoms is highly variable from study-to-study: Binder et al. (1997) [15] reported post-acute symptoms in 7–8% of cases, while Rimel et al. [6] reported 33%. These symptoms have been known to last several months or even years [8, 16–20].

Two meta-analyses conducted by Bélanger and Vanderploeg [7] and Broglio and Puetz (2008) [21] on studies dealing with sports concussion identified the impact of sports concussion on a number of neurocognitive functions in the initial hours, days and, in some cases, weeks post-injury. The studies pointed out deficits in four areas: (1) attention, (2) memory and learning, (3) overall cognitive function and (4) executive function. Generally, most participants appear to recover fully during the months following the concussion. Some individuals, however, experience long-term effects and/or slower recovery. While most of the existing research has focused on the acute phase post-concussion, recent studies conducted using neuroimaging techniques support the idea that certain athletes experience an impact over the long-term.

One of the key considerations in studying sports concussion is the tool used to assess the impaired cognitive functions. Standard neuropsychological assessment is considered sensitive to the immediate effects of concussion in certain athletes [22]; it is recognized as being more sensitive than regular neurological or radiological testing [23]. If neuropsychological assessment is to detect the effects of sports concussion, it must be sensitive to the symptoms of mild brain injury [24–26]. Recently, Broglio et al. [27] noted that event-related potentials (ERPs) were useful in identifying areas of cognition that remained dysfunctional for an extended period of time post-concussion and that would otherwise go undetected by standard neuropsychological tests.

The short- and long-term effects of sports concussion have been observed in several related studies that have been conducted using sophisticated neuroimaging techniques such as functional magnetic resonance imaging (fMRI) [28–31] and ERPs [27, 32–34]. While these technologies are essential in demonstrating the effects of sports concussion in the brain, they are difficult to use and are not readily transported into ‘everyday’ environments, such as schools with sports and education programmes (SEPs). There is still a need, therefore, to further develop tools for assessing the cognitive effects of sports concussion that are both user-friendly and sufficiently sensitive.

Virtual reality

By means of immersive virtual reality, users can interact in real time with a 3-dimensional, computer-simulated environment that mirrors daily life [35–38]. This makes it a revolutionary tool. Users enter the immersion by wearing a head-mounted display (HMD) onto which the virtual environment is projected. The user’s head movements are sensed by a detection system integrated into the HMD and converted into computerized data.

Studies using immersive neuropsychological assessments to study people with mTBI are few. The advantages offered by virtual reality, such as greater sensitivity and ecological validity, make research in this area a promising endeavour. Testing in virtual reality gauges the true functioning of subjects in environments where they are left to their own devices and allowed to behave naturally. Additionally, automatic scoring reduces the number of errors that might skew the results. By its very nature, testing in virtual reality detects subtle deficits, which are often imperceptible in traditional assessments [36, 37, 39–43]. The use of virtual reality techniques in attention and inhibition testing is therefore a promising avenue for improved identification of cognitive deficits following sports concussion.

Only recently has virtual reality become a tool for studying people with traumatic brain injury (TBI). Most studies on this topic have been conducted on adults and most have focused on a limited number of cognitive domains, such as motor and balance rehabilitation [44–51], social problem-solving [52], community living skills [53] and car driving [54]. These studies have demonstrated the advantages of virtual reality on adults with moderate or severe TBI.

As for studies on children with TBI, those using virtual reality as an assessment tool are relatively scarce [55, 56]. Some studies have demonstrated the utility of virtual reality in cases of moderate or severe TBI [39, 40], but not the mild type (mTBI). (The only two studies to have used virtual reality to assess people with mTBI were both conducted on adults.). Slobounov et al. (2006) [57] showed that advanced virtual reality technology, used in combination with balance and motion tracking technologies, was able to detect residual symptoms of concussion symptoms in university athletes. More recently the same research team (Slobounov et al. 2010) [58] studied the effects of concussion using fMRI in combination with a virtual reality paradigm in adult athletes. In summary, while virtual reality has met with success in detecting subtle cognitive deficits resulting
from sports concussion, further studies are needed, both on adults and on children. To the best of the authors’ knowledge, the present study is the first to focus on adolescents.

The objective of this study is to compare performance in attention and inhibition tests (both traditional and virtual) between two groups of adolescents enrolled in an SEP: those who have sustained a concussion and those who have not.

Method

Participants

Group 1 (sports concussion) was composed of 25 adolescents enrolled in an SEP at the Académie Estacades in Trois-Rivières, Québec, Canada. All participants suffered a concussion while playing their sport at some time in the 2 years preceding the study. The time between concussion and evaluation ranged from 1–24 months (mean = 11.71 months, SD = 8.80 months). The most common sports in which the participants had been injured were hockey, basketball, and soccer. The sports concussion group was made up of 15 boys and 10 girls, with a mean age of 13.64 years (SD = 1.11 years). All participants in the group suffered a Grade 1 concussion (Cantu Concussion Grading Guideline, 2001 [59]). By this definition, they experienced no loss of consciousness (LOC) due to the injury and any post-traumatic amnesia lasted under 30 minutes. Concussions were of the simple type, which is defined by the Summary and Agreement Statement of the 2nd International Conference on Concussion in Sport (McCrorry et al. 2005 [60]) as a concussion for which associated symptoms resolved within 7–10 days without complications. Inclusion criteria also included commonly accepted clinical symptoms of mTBI taken from SCAT2 (http://www.cces.ca/files/pdfs/SCAT2[1].pdf) such as headache, ‘pressure in head’, neck pain, nausea or vomiting, dizziness, difficulty concentrating, irritability, etc. [14].

Group 2 (control) consisted of 25 adolescents who were also enrolled in the SEP but who did not sustain a sports concussion in the 2 years preceding the study. This group was also made up of 15 boys and 10 girls, this time with a mean age of 13.76 years (SD = 1.13 years).

All participants followed the normal SEP curriculum and had no history of neurological, psychological or learning disabilities. The two groups were equivalent with respect to age [t(48) = −0.38, p < 0.05] and gender. All participants in the study were francophone.

Measures

Sense of presence and cybersickness questionnaires. In order to verify the quality of the immersion during the virtual neuropsychological test, we administered two questionnaires to each participant. The questionnaires covered two important factors in virtual-reality studies: sense of presence and cybersickness. Sense of presence refers to the propensity to respond to virtually generated sensory data as if they were real [61]. Cybersickness denotes symptoms that may be felt during or after the participant’s experience in virtual reality, such as nausea or eye strain.

The first questionnaire, the Presence Questionnaire, was developed by Witmer and Singer (1998) [62] and revised by the UQO Cyberpsychology Laboratory, 2004 [63]. It consists of 18 questions answered on a Likert-type scale ranging from 0 (‘not at all’) to 7 (‘completely’). For the purposes of this study, a customized version of the questionnaire was used with eight items expressly adapted for this adolescent study population. The psychometric validity of the questionnaire is supported by the Cronbach’s alpha of 0.78 for this study sample.

The second questionnaire, the Post-Exposure Symptom Checklist, was developed by Kennedy et al. (1993) [64] and later translated into French and revised by the UQO Cyberpsychology Laboratory (2002) [65]. It consists of 16 items answered on a Likert-type scale ranging from 0 (‘none’) to 3 (‘severe’). The variables measured by this questionnaire are the number of cybersickness and the mean intensity of cybersickness as experienced by participants. The psychometric validity of the questionnaire is supported by a Cronbach’s alpha of 0.87 for this study sample. The complete list of symptoms can be found in Table I.

Neuropsychological test: Traditional

To test attention and inhibition functions in a traditional setting, the VIGIL-CPT (Vigil Continuous Performance Test, Cegalis & Bowlin, 1991 [66]) was used. In this computerized test, letters appear one at a time in the centre of a screen, changing at an interval that is kept constant throughout the test. The participant is required to click the mouse each time the letter K appears after being immediately preceded by the letter A. The 6-minute test presents a total of 300 stimuli, 60 of which require a response. In clinic and in research, the VIGIL-CPT is a recognized measure of sustained attention, vigilance, impulsivity and reaction time [67]. The three variables measured in the traditional test were (1) the number of omissions (i.e. failure to respond to the letter K when immediately preceded by the letter A), (2) the number...
of commissions (i.e., responding to the letter K when not preceded by the letter A or responding to another letter) and (3) the mean reaction time in milliseconds. For each of the three variables, performance can be tracked over time by splitting the 6-minute test into three blocks of 2 minutes each. A comparison of the scores in the three blocks serves as a measure of the effects of fatigue as the test progresses.

Neuropsychological test: Virtual

The immersive test of attention and inhibition was first developed by Rizzo et al. [39]. It was revised by the Digital MediaWorks team (http://www.dmw.ca/) under the name ClinicaVR: Classroom-CPT. The test is identical to the traditional VIGIL-CPT except for the environment in which it is administered: instead of being presented on a computer screen, the stimuli appear on a whiteboard situated in a virtual classroom. The virtual classroom features objects and people commonly found in real classrooms, such as the blackboard, desks, a teacher and students. Participants were immersed in the virtual environment by wearing an Emagin Z800 HMD with the ability to monitor the wearer’s head movements. Participants were able to look 360° around themselves as well as up and down in the virtual environment. Typical classroom sounds were played to the participant through headphones integrated into the HMD. Throughout the duration of the virtual test, the wearer experienced auditory and visual distractions typical of a real classroom, such as a knock at the door, a bell announcing the end of class, children laughing outside and a visit from the principal. The four variables measured in the virtual test were (1) the number of omissions, (2) the number of commissions, (3) the mean reaction time

<table>
<thead>
<tr>
<th>Symptoms</th>
<th>Frequency</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Chi square</th>
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<td>General discomfort</td>
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<td>10</td>
<td>3</td>
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<td>7.22*</td>
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<tr>
<td></td>
<td>Gr 2</td>
<td>21</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Fatigue</td>
<td>Gr 1</td>
<td>4</td>
<td>13</td>
<td>6</td>
<td>2</td>
<td>8.18*</td>
</tr>
<tr>
<td></td>
<td>Gr 2</td>
<td>10</td>
<td>14</td>
<td>1</td>
<td>0</td>
<td></td>
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<tr>
<td>Headache</td>
<td>Gr 1</td>
<td>14</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>5.58</td>
</tr>
<tr>
<td></td>
<td>Gr 2</td>
<td>18</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Eye strain</td>
<td>Gr 1</td>
<td>4</td>
<td>10</td>
<td>8</td>
<td>3</td>
<td>3.85</td>
</tr>
<tr>
<td></td>
<td>Gr 2</td>
<td>8</td>
<td>12</td>
<td>4</td>
<td>1</td>
<td></td>
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<tr>
<td>Difficulty focusing</td>
<td>Gr 1</td>
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<td>8</td>
<td>2</td>
<td>3</td>
<td>5.86</td>
</tr>
<tr>
<td></td>
<td>Gr 2</td>
<td>17</td>
<td>8</td>
<td>0</td>
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<td></td>
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<tr>
<td>Increased salivation</td>
<td>Gr 1</td>
<td>14</td>
<td>9</td>
<td>2</td>
<td>0</td>
<td>6.78*</td>
</tr>
<tr>
<td></td>
<td>Gr 2</td>
<td>22</td>
<td>3</td>
<td>0</td>
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<td></td>
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<tr>
<td>Sweating</td>
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<td></td>
<td>Gr 2</td>
<td>22</td>
<td>3</td>
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<td>0</td>
<td></td>
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<tr>
<td>Nausea</td>
<td>Gr 1</td>
<td>20</td>
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<td>1</td>
<td>0</td>
<td>5.56</td>
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<tr>
<td></td>
<td>Gr 2</td>
<td>25</td>
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<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Difficulty concentrating</td>
<td>Gr 1</td>
<td>11</td>
<td>11</td>
<td>3</td>
<td>0</td>
<td>9.39**</td>
</tr>
<tr>
<td></td>
<td>Gr 2</td>
<td>21</td>
<td>4</td>
<td>0</td>
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<tr>
<td>‘Fullness of the head’</td>
<td>Gr 1</td>
<td>10</td>
<td>8</td>
<td>7</td>
<td>0</td>
<td>8.44*</td>
</tr>
<tr>
<td></td>
<td>Gr 2</td>
<td>16</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Blurred vision</td>
<td>Gr 1</td>
<td>15</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>5.71</td>
</tr>
<tr>
<td></td>
<td>Gr 2</td>
<td>20</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Dizziness with eyes open</td>
<td>Gr 1</td>
<td>18</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>5.52</td>
</tr>
<tr>
<td></td>
<td>Gr 2</td>
<td>24</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Dizziness with eyes closed</td>
<td>Gr 1</td>
<td>17</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>4.78</td>
</tr>
<tr>
<td></td>
<td>Gr 2</td>
<td>22</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Vertigo</td>
<td>Gr 1</td>
<td>22</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td>Gr 2</td>
<td>24</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>‘Stomach awareness’</td>
<td>Gr 1</td>
<td>23</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>Gr 2</td>
<td>22</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Burping</td>
<td>Gr 1</td>
<td>24</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1.02</td>
</tr>
<tr>
<td></td>
<td>Gr 2</td>
<td>25</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</tr>
</tbody>
</table>

* p < 0.05; ** p < 0.01.
in milliseconds and (4) the number of left–right head movements (i.e. those made along the horizontal axis). As in the traditional VIGIL-CPT, it was possible to obtain performance scores for the 6-minute test in three blocks of 2 minutes, thereby tracking performance over the course of the test.

Procedure

Students participated individually in testing sessions during regular class hours. The order of the traditional and virtual tests was counterbalanced across participants to prevent skewing of the results due to practice or fatigue effects. The data were collected over a period of 5 weeks. The study procedure was approved by the Human Research Ethics Committee of the University of Québec at Trois-Rivières.

Results

Sense of presence and cybersickness questionnaires

This section presents the results for sense of presence and cybersickness experienced by participants in the virtual test.

On average, individuals in the sports concussion group experienced roughly the same sense of presence as those in the control group (see Table II); the ANOVA showed no difference between the groups for this variable \(F(1,48) = 1.61, p > 0.05\). All participants felt ‘moderately’ present during the virtual test. Since there was no correlation between sense of presence score and the virtual test scores (omissions \(r = 0.03, p > 0.05\); commissions \(r = -0.04, p > 0.05\); reaction time \(r = 0.06, p > 0.05\); left–right head movements, \(r = -0.06, p > 0.05\)), this study was able to compare performance between the two groups for the immersive test.

There was no correlation between cybersickness score and virtual test scores (omissions \(r = 0.14, p > 0.05\); commissions \(r = -0.15, p > 0.05\); reaction time \(r = 0.22, p > 0.05\); left–right head movements, \(r = 0.08, p > 0.05\)). The cybersickness intensity scores showed that all participants, on average, experienced ‘mild’ cybersickness. Table I shows the frequency of reported cybersickness by group. The sports concussion group reported more symptoms of cybersickness \(F(1,48) = 12.73, p < 0.001\) than the control group (see Table II). The intensity of the cybersickness was higher for the sports concussion group \(F(1,48) = 23.50, p < 0.001\) than for the control group (see Table II). The score from the cybersickness questionnaire was then co-varied in comparative analysis of the groups for the virtual test scores.

Group comparisons: Traditional vs immersive neuropsychological test

This section presents the results of group comparisons performed on the traditional and virtual neuropsychological test scores. First, results are given for ANOVAs performed on the three variables measured in the traditional VIGIL-CPT: omissions, commissions and reaction time. Secondly, results are given for the ANCOVAs performed on the four variables measured in the virtual version of the CPT: omissions, commissions, reaction time and left–right head movements; scores from the cybersickness questionnaire were co-varied in these analyses. Table II shows the means and standard deviations for all variables as well as the results from the statistical analysis.

Table II shows that there was no significant difference between the two groups for any of the three variables in the traditional VIGIL-CPT.

<table>
<thead>
<tr>
<th></th>
<th>Group 1 Sports concussion ((n = 251))</th>
<th>Group 2 Control ((n = 25))</th>
<th>(F) Co-variable (Cybersickness)</th>
<th>(F)</th>
<th>Partial Eta squared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sense of presence</td>
<td>3.44 (SD = 0.94)</td>
<td>3.42 (SD = 0.73)</td>
<td>0.01</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>Cybersickness (number of symptoms)</td>
<td>6.24 (SD = 3.63)</td>
<td>3.32 (SD = 1.89)</td>
<td>12.73***</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>Cybersickness (intensity)</td>
<td>1.57 (SD = 0.44)</td>
<td>1.23 (SD = 0.14)</td>
<td>13.79***</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>Traditional VIGIL-CPT Omissions</td>
<td>4.79 (SD = 7.52)</td>
<td>3.12 (SD = 3.26)</td>
<td>1.04</td>
<td>0.02</td>
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</tr>
<tr>
<td>Traditional VIGIL-CPT Commissions</td>
<td>4.54 (SD = 3.59)</td>
<td>6.40 (SD = 4.53)</td>
<td>2.52</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Traditional VIGIL-CPT Reaction time</td>
<td>324.49 (SD = 58.38)</td>
<td>320.33 (SD = 39.00)</td>
<td>0.09</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>ClinicaVR: Classroom Omissions</td>
<td>3.36 (SD = 3.26)</td>
<td>1.96 (SD = 2.17)</td>
<td>0.02</td>
<td>2.23</td>
<td>0.05</td>
</tr>
<tr>
<td>ClinicaVR: Classroom Commissions</td>
<td>5.96 (SD = 6.47)</td>
<td>3.88 (SD = 2.65)</td>
<td>4.10*</td>
<td>5.34*</td>
<td>0.10</td>
</tr>
<tr>
<td>ClinicaVR: Classroom Reaction Time</td>
<td>377.23 (SD = 42.54)</td>
<td>380.08 (SD = 46.67)</td>
<td>3.64†</td>
<td>1.22</td>
<td>0.03</td>
</tr>
<tr>
<td>ClinicaVR: Classroom Left–right head movements</td>
<td>72.28 (SD = 69.98)</td>
<td>35.04 (SD = 21.29)</td>
<td>0.53</td>
<td>6.64**</td>
<td>0.12</td>
</tr>
</tbody>
</table>

*\(p < 0.05\); **\(p < 0.01\); ***\(p < 0.001\); † = statistical tendency between 0.06–0.09.
However, significant differences did exist between the groups for two of the four variables in the virtual version of the CPT: number of commission errors and number of left–right head movements. (These differences were observed after the effect of cybersickness was removed.)

Since significant differences were observed for commission errors and head movements in the virtual test, supplementary analyses were conducted on the respective groups’ test scores for these variables over the three 2-minute blocks. (Recall that scores from the VIGIL-CPT, in both the traditional and the immersive versions, can be examined by dividing the 6-minute test into three blocks of 2 minutes each, thus obtaining a measure of performance over time.)

Figure 1 shows the number of commission errors by group for the three time blocks. Since there were not enough participants for a multivariate analysis, an ANOVA was used to compare performance between the groups in each time block. A Bonferroni correction was applied with a significance threshold of 0.017 to avoid Type I errors. The analyses showed no significant difference between the two groups; the significance threshold of 0.04 was reached only in Block 3. In summary, the following trend emerged from the statistical analysis: the control group tended to make fewer commission errors over time, whereas the sports concussion group made the same number of errors all throughout the test.

Figure 2 shows the number of left–right head movements for the three time blocks by group, using the same statistical approach as above. The analyses showed a significant difference between the groups for left–right head movements in Block 1 \( F(1,48) = 4.27, \ p = 0.01 \) and in Block 3 \( F(1,48) = 8.84, \ p = 0.019 \) and a statistical trend was observed in Block 2 \( F(1,48) = 0, \ p = 0.06 \). It can be concluded that the sports concussion participants
made more head movements than control participants throughout the duration of the test.

**Discussion**

The goal of the present study was to determine if an attention and inhibition test administered in virtual reality (*ClinicaVR: Classroom-CPT*) was sensitive enough to detect the subtle effects of sports concussion in a group of adolescents enrolled in an SEP. The virtual environment represents a revolutionary assessment tool for neuropsychological research, yet it remains under-exploited, especially in studies on children with mTBI. These results support the hypothesis that *ClinicaVR: Classroom-CPT* is sensitive enough to detect subtle effects in the sports concussion group when compared to the control group.

The virtual test specifically revealed a difference between the groups in the number of commission errors and the number of left–right head movements; both these variables may be interpreted as deficits of inhibition. The data are consistent with previous studies that have demonstrated a link between sports concussion and cognitive deficits of this type [26, 68–70].

Given that subtle cognitive deficits typically improve within 3–6 months of the accident [7, 71, 72], it is somewhat surprising that they were detected in these sports concussion participants. Few studies have dealt with the long-term effects of sports concussion. Further research into this topic is needed and the sensitivity of the tool will be a key consideration in this. A handful of studies using fMRI [30] and event-related potentials [27, 34] point to the existence of long-term cognitive effects of sport concussion in adults.

Sports-concussion group experienced more cybersickness than the control group, both in the number of cybersickness and in the intensity thereof. Specifically, the sports concussion group reported the following five symptoms more frequently: general discomfort, fatigue, increased salivation, difficulty concentrating and ‘fullness of the head’. Generally speaking, the nature of these subjectively reported symptoms is consistent with the kind of cognitive deficits detected by the virtual test.

Attention and inhibition problems among adolescents were found to be greater in the virtual CPT than in the traditional version; in fact, the traditional version showed no difference between the groups for these deficits. The immersive assessment approach thus appears more sensitive to the effects of sports concussion than the traditional approach. It is possible that the superior sensitivity of *ClinicaVR: Classroom-CPT* may be due to the ‘ecological’ nature of the tool; this means that it closely represents real-life experiences, thus placing greater demands on the participant’s capacities of attention and inhibition. The question of whether the ecological representativeness of the tool accounts for these results is one that must be addressed by future research. Such research should illustrate, first, the relationship between the two assessment approaches (traditional and virtual) and, secondly, the relationships between these approaches and existing ecological measures such as the Behavior Rating Inventory of Executive Function [73] and observed behaviours in real-life classrooms. Perhaps it is not the case that the virtual CPT is more ecological than the traditional version, but that it is simply more complex given that it requires participants to process more information.

At the very least, it can be said that *ClinicaVR: Classroom-CPT* seems to respond well to sensitivity criteria for detecting the subtle effects of sports concussion.

The results contribute to a body of existing literature that has demonstrated the utility of the virtual classroom in studying children and adolescents with ADHD [74–79]. Importantly, the virtual classroom also has the benefit of being enjoyable to participants [78, 80]. The use of *ClinicaVR: Classroom-CPT* need not be limited to the population in our study: it would be equally advantageous in future clinical neuropsychological research on other populations.

The results generated in the present study could serve as the basis for a subsequent prospective study. The study would be designed in such a way that the sensitivity of *ClinicaVR: Classroom-CPT* in detecting the subtle effects of sports concussion would be verified by assessing, at the beginning of the school year, basic functions in all students enrolled in the SEP, and by subsequently performing short- and long-term reassessments on those students who sustain concussions in the future. This proposed study design is consistent with recommendations made in related studies [23] and could aid in preventing faulty attribution, i.e. the phenomenon of injured students being viewed as having other diagnosis such as hyperactivity or conduct disorders [81].

**Conclusion**

Neuropsychological assessment, used as a tool for detecting cognitive deficits resulting from sports concussion, is recommended by experts in the field as part of a sports concussion protocol [82–84]. Assessments based on computerized tests are recommended over traditional ones (e.g. paper and pencil tests) because they present a number of...
advantages [23, 85]). One such advantage, easy reproducibility, makes it possible to conduct multiple studies at the same time or in different locations; another is the fact that no specialized training is required to operate the equipment. ClinicaVR: Classroom-CPT meets all these criteria and is also much more affordable and user-friendly than neuroradiological technologies. For all these reasons, ClinicaVR: Classroom-CPT is a compelling choice for the study of sports concussion.

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