

Assessment of verbal and visual episodic memory, post-concussive complaints, and their relationship following mild traumatic brain injury

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Neuropsychological deficits following mild traumatic brain injury (mTBI) are usually discrete and sometimes hard to detect. This study aimed to evaluate relationships between episodic memory and post-concussive symptoms (PCS). The sample was composed of 55 participants aged between 20 to 64, including 25 patients with mTBI and 30 healthy control participants. Participants completed the *Rey Auditory Verbal Learning Test*, the *Rey-Osterrieth Complex Figure*, and other questionnaires measuring the intensity of memory complaints, fatigue, and sleep quality. An analysis of the data revealed: 1) no significant differences between both groups in episodic memory performance, in either the verbal or visual modalities; 2) that the intensity of PCS was significantly higher than expected in the normal population (i.e., no PCS symptoms); and 3) no significant association between PCS and memory performance. Those results suggest that, even though patients with mTBI complain about significant memory difficulties and PCS, neuropsychological tests most used in clinics do not objectify those memory complaints.

Keywords: mild traumatic brain injury, episodic memory, *Rey-Osterrieth Complex Figure*, *Auditory Verbal Learning Test*, post-concussion symptoms

Les déficits neuropsychologiques à la suite d'un traumatisme craniocérébral léger (TCCL) sont généralement discrets et parfois difficilement détectables. Le but de cette étude était d'explorer le lien entre la mémoire épisodique et les symptômes post-commotionnels (SPC). L'échantillon était composé de 55 patients âgés entre 20 et 64 ans, où 25 ont subi un TCCL et où les 30 autres sont inclus dans le groupe contrôle. Les participants ont réalisé le *Rey Auditory Verbal Learning Test*, le *Rey-Osterrieth Complex Figure* et d'autres questionnaires mesurant l'intensité des plaintes mnésiques, de la fatigue et de la qualité du sommeil. L'analyse des données a pu mettre en évidence : 1) une absence de différence significative des performances mnésiques, de modalités verbale et visuelle entre les deux groupes; 2) l'intensité significative des SPC par rapport à ce qui est attendu dans la population normale (c.-à-d., aucun SPC); et 3) une absence de lien entre les SPC et les performances mnésiques. Ces résultats suggèrent que, malgré le fait que les patients TCCL se plaignent de difficultés de mémoire et de SPC importants, les tests neuropsychologiques les plus utilisés en clinique ne permettent pas d'objectiver ces plaintes mnésiques.

Mots-clés : traumatisme craniocérébral léger, mémoire épisodique, *Rey-Osterrieth Complex Figure*, *Rey-Taylor Auditory-Verbal Learning Test*, symptômes post-commotionnel

Mild traumatic brain injury (mTBI) is a neurological disorder, which occurs when the brain functioning is disrupted due to an external force (Menon et al., 2010), is a public health concern. Even though it is the mildest category of traumatic brain

injury, it is the cause of many medical consultations in adults (Truchon et al., 2018). It accounts for between 80% and 90% of all TBIs in the global adult population (Skandsen, 2019). Around 42 million people worldwide suffer a mTBI every year (Gardner, 2015). Following mTBI, patients express post-concussive symptoms (PCS). Most reported complaints in the first three months post-accident (i.e., acute phase) are memory impairment, fatigue, and sleep disturbance. These symptoms may persist over time and become chronic, beyond three months (i.e., post-acute phase; Cassidy et al., 2014).

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Episodic memory impairment following mTBI

Episodic memory (EM) is:

An information processing system that (a) receives and stores information about temporally dated episodes or events, and about temporal-spatial relations among these events, (b) retains various aspects of this information, and (c) upon instructions transmits specific retained information to other systems, including those responsible for translating it into behavior and conscious awareness. (Tulving, 2002)

EM impairment in the verbal or visual modality refers to either the inability to learn new information (i.e., anterograde memory) or to recall a memory (i.e., retrograde memory) on a long-term basis. Memory performance is frequently impaired following mTBI and is most often the subject of patient complaints in the acute phase (Cassidy et al., 2014; Tayim et al., 2016) and post-acute phase (Dikmen et al., 2010). A meta-analysis published by Bélanger et al. (2005) revealed a significant decrease in delayed memory performance and the ability to learn new information in patients who have suffered mTBI. These results are supported by a study from Dikmen and colleagues (2017), which has shown that the memory performance in verbal modality is significantly lower in patients with mTBI than that of the healthy control group one month after the accident. Similarly, a study by Tayim and collaborators (2016) shows that mTBI affects short-term verbal memory. Regarding visual memory, studies have shown an alteration of this form of memory as, compared to a control group, patients who have undergone a mTBI have lower scores (Gaines et al., 2015; L'Écuyer-Giguère et al., 2019). In addition, patients with mTBI are aware of their memory difficulties, which are their main complaint (Anderson & Schmitter-Edgecombe, 2009), as a decrease in memory efficiency in EM disrupts their daily functioning in terms of managing simple (e.g., attending appointments on time) and complex tasks (e.g., at work; Carroll et al., 2004; Carroll et al., 2014; Dikmen et al., 2010).

To better understand the causes of these memory deficits, it is important to determine the brain areas most often affected by mTBI. The areas most affected following mTBI are generally the frontal and temporal lobes (Phillips et al., 2017). These two regions play a key role in learning and recall processes, which explains why memory is often impacted after this type of injury. Various neuroimaging studies have contributed to a better understanding of the impact of mTBI on memory. Levine (2002) compared the brain activation of a control group and a TBI group of any severity when performing a memory task. No

significant differences were found between the two groups in behavioral test performance. In terms of brain activation, during the execution of the task, the two groups used the frontal, temporal and parietal regions associated with the restitution of an episodic event. However, in the TBI patients' group, the frontal and occipital regions, as well as the anterior cingulate regions, were additionally solicited. The greater activations reported in the mTBI group could be explained by a neural reorganization due to the injury. Similarly, altered diffusivity of the hippocampal subregions, indicative of altered microstructural integrity of grey matter, has been found in mTBI patients (Leh et al., 2017).

Relationship between post-concussive symptoms and memory following mTBI

In addition to possible damage to the brain areas responsible for mediating memory function, other factors concomitant with mTBI may impair proper memory functioning. These factors include the presence of PCS. In this study, we will focus on fatigue and sleep, the most reported symptoms in the acute phase (Ponsford & Sinclair, 2014; Wylie & Flashman, 2017).

Fatigue

Fatigue is a multidimensional phenomenon, with four main subtypes: cognitive fatigue, physical fatigue, emotional fatigue, and stress-related fatigue (Wylie & Flashman, 2017). Cognitive fatigue results from the extra effort required for the brain to process information and subsequently causes slowness (McAllister et al., 1999; Ozen et al., 2013; Wylie & Flashman, 2017). Performing a cognitive task in an intense or prolonged manner generates mental fatigue.

This phenomenon is one of the major sequelae of mTBI (Johansson & Rönnbäck, 2017; Ponsford et al., 2019; Schiehser et al., 2016; Stullemeijer et al., 2006; Wylie & Flashman, 2017). A significant number of patients with mTBI report mental fatigue after their accident, which is considered subjective and difficult to define and measure (Iverson et al., 2010). This decrease in energy plays a major role in the ability to learn new information, memorize it, and recall it (Jonasson et al., 2018). All these memory performances also require greater attentional demands and an increased neuronal energy cost (Jonasson et al., 2018; McAllister et al., 1999). Overall, fatigue is characterized by a rapid decline in energy and longer recovery time and can become a long-term problem impacting the return to work, school, and resumption of daily activities and the quality of life of individuals who have undergone mTBI (Johansson et al., 2017; Stullemeijer et al., 2006; Wylie & Flashman, 2017).

Sleep disorders

Following mTBI, 30% to 70% of patients suffer from sleep disorders (Viola-Saltzman & Musleh, 2016). These patients describe their complaints as insomnia (i.e., difficulty falling asleep or staying asleep) or drowsiness (i.e., strong urge to sleep). Sleep disorders may result from derangement of the sleep-wake cycle or secondary factors such as depression and anxiety (Losoi et al., 2016; Ponsford & Sinclair, 2014; Wylie & Flashman, 2017). In a study by Ponsford and Sinclair (2014), following brain injury of any severity, patients often had higher levels of sleepiness, increased need for naps, longer sleep latency, and significantly poorer sleep quality than the control group. This may subsequently disrupt the recovery and resumption of lifestyle habits (Losoi et al., 2016; Wylie & Flashman, 2017). Disruption of the sleep-wake regulation center could accentuate physical and cognitive disorders, particularly memory disorders. Indeed, sleep plays a key role in the consolidation of learning and optimizes memory (Gais, 2006). During slow-wave sleep, there is a neuronal reactivation of the information learned, reinforcement of synapses, and a transfer of this activation to the cortical level, which makes it possible to keep track of memories over the long term (Frankland & Bontempi, 2005). Similarly, sleep is also involved in the association of knowledge learned differently (e.g., information integration and generalization of learning; Ellenbogen et al., 2009). Thus, sleep improves recall performance and saves learning time (Mazza, 2016). Wheaton (2011) studied the impact of poor sleep quality in a population of healthy subjects. He demonstrated that a decrease in the amount of sleep leads to drowsiness and fatigue, which are responsible for concentration difficulties and therefore memory difficulties. Several studies have highlighted the relationship between sleep and fatigue. The study by Schiehser et al. (2016) looked at the relationship between these two PCS following mild to moderate TBI and noted that sleep quality predicts cognitive fatigue. No study so far has shown a causal relationship between sleep quality and cognitive fatigue. We cannot conclude that one causes the other. However, what could be noted is that sleep quality impacts fatigue and is likely to exacerbate memory problems.

Objectives and hypotheses

In short, few studies have evaluated the post-acute impacts of mTBI on EM functioning, and none, to our knowledge, have explored the relationship between PCS and EM. Thus, the aims of this study were to 1) assess the memory performance in the visual and verbal modalities; 2) assess the memory complaints and PCS of patients who have undergone mTBI; and

3) explore the relationship between PCS, especially fatigue and sleep, and memory performances.

To assess EM performance following mTBI, we compared mTBI patients with a matched control group, using the *Rey-Taylor Auditory-Verbal Learning Test* (RAVLT) to assess verbal memory, and the *Rey-Osterrieth Complex Figure* (ROCF) test to assess visual memory. The review of the literature led us to hypothesize that the mTBI group would have lower performance in verbal and visual memory than the control group. To address the second objective, we compared the PCS scores of the mTBI patients with what is normally expected in the healthy population (i.e., the absence of PCS). We expected a significantly higher memory complaint, fatigue level, and poorer sleep quality than expected in a healthy population without mTBI. In addition, we expected to find a relationship between memory performance in both the verbal and visual modalities and PCS. In this sense, PCS should predict RAVLT and ROCF scores.

Method

Participants

mTBI patients.

Inclusion criteria. Patients had to be 18 years of age or older, fluent in English or French, and medically diagnosed with mTBI by a physician. To be included in the study and be defined as mTBI, patients were required to have a *Glasgow Coma Scale* (GCS) score between 13 and 15, 30 minutes after the injury or later upon presentation in the emergency department. The GCS tool is used to reliably measure a person's level of consciousness after a traumatic brain injury. The GCS assesses a person based on their ability to perform eye movements (i.e., 5 points), speak (i.e., 5 points), and move their body (i.e., 5 points), for a total of 15 points. Participants also presented one or more of the following signs: 1) confusion or disorientation; 2) loss of consciousness for less than 30 minutes; 3) post-traumatic amnesia for less than 24 hours; or 4) other transient neurological abnormalities (e.g., focal signs, convulsions, intracranial lesions not requiring surgery). All patients included in this study were symptomatic and followed in an out-patient mTBI clinic for symptoms management.

Exclusion criteria. mTBI patients with neurological disorders that weren't associated with mTBI, an active psychiatric disorder (e.g., psychosis), a history of TBI or substance abuse in the past five years, neurodevelopmental disorders (e.g., ADHD), or an intellectual disability were not included in the study. A history of depression or anxiety disorder was not an exclusion criterion as well as previous mild

traumatic brain injuries, as this is a possible contributing factor to the persistence of PCS (Carroll et al., 2004; Kumar et al., 2014).

Control participants. Patients in the control group, aged 18 years or older and fluent in English or French, with no previous traumatic brain injury, were recruited from the community using classified ads. The exclusion criteria were the same as for the mTBI patients.

Procedure

In this retrospective study, patients were referred from the Emergency Department of the Montreal General Hospital of the McGill University Health Centre. Within the first month following their accident and visit to the Emergency Department, patients were diagnosed with mTBI by specialists at the Montreal General Hospital mTBI Outpatient Clinic and according to the *World Health Organization Task Force criteria* (Cassidy et al., 2004). Patients were then referred for neuropsychological assessment the following week. A neuropsychological evaluation was carried out between four and eight post-accident weeks. All patients performed three hours assessment during which they had to complete questionnaires and neuropsychological tests such as 1) the *Rivermead Post-concussion questionnaire* (RPQ); 2) the *Vocabulary and Matrix Reasoning*, two subtest-form of the *Wechsler abbreviated Scale of Intelligence* (WASI-II); 3) the *Pittsburg Sleep Quality Index* (PSQI); 4) the *Multidimensional Fatigue Inventory* (MFI); 5) the *Digit Span*, a subtest from the *Wechsler Adult Intelligence Scale* (WAIS-IV); 6) RAVLT; and 7) ROCF. Those tests were administered in a standardized order avoiding interference from the verbal and visual modalities between delays for the memory tests.

Data collection. Demographic and medical data related to the accident, as age, education, and sex, were collected retrospectively from patients' medical records. It included the mechanism of injury (e.g., motor vehicle accident, fall, assault, suicide attempt), the presence of loss of consciousness and post-traumatic amnesia, and the GCS score. The neuropsychological data of the clinical group (i.e., RAVL and ROCF), PCS complaints (i.e., RPQ), and sleep and fatigue measures (PSQI and MFI) were collected from the Audrit and al. research trial (2021). To evaluate EM, both the RAVLT and the ROCF were administered in the standardized procedure for replication purposes because they are the most popular neuropsychological measures of verbal and visual memory. For the control group, assessments were performed at the Marie-Victorin Pavilion or the Laval campus of the Université de Montréal.

Recruitment of outpatients with mTBI took place between November 2015 and October 2017 at the Montreal General Hospital, a tertiary trauma care center. All volunteers gave their consent before participating in the experiment. The Research Ethics Board of the McGill University Health Centre and the Research Ethics Board for Education and Psychology of the Université de Montréal approved this study.

Instruments.

Rey-Taylor Auditory-Verbal Learning Test (RAVLT). This EM test is presented in the form of a list of 15 words. The list is learned in five successive presentations, followed by immediate recall after each presentation, then an interference test involving the presentation and recall of another 15-word list, followed by immediate recall and recognition of the original list. Then, 20 min after a delayed recall of the original list and, in the end, a delayed recognition test. The RAVLT assesses immediate memory span, new learning, susceptibility to interference, and recognition memory (Spren & Strauss, 1998). It also allows for the construction of a learning curve as the tests progress. A total score between 0 and 15 could be obtained for each trial in the learning phase and the three forms of recall (i.e., immediate, delayed, and recognition). A high score indicates better verbal memory performance. For the present study, scores of the learning curve (i.e., R1, R2, R3, R4, and R5), immediate recall, delayed recall, and recognition were computed.

Rey-Osterrieth Complex Figure test (ROCF). This neuropsychological test allows for the objective evaluation of episodic visual/visuospatial memory with the help of a complex drawing. It is composed of 18 elements organized in three parts: an overall shape, external elements, and internal elements (Crowin and Bylsma, 1993; Rey, 1941; Shin and all, 2006). ROCF allows the evaluation of different cognitive processes, such as planning, spatial organization, visuo-perceptive and construction skills, and memory with delayed recall (Spren & Strauss, 1998). The test is carried out in four stages. First, the subject is asked to copy the figure as well as possible (i.e., incident learning), followed by an immediate recall three minutes later. At the immediate recall after three minutes, the participant is asked to redraw what he remembers from the drawing. Then, a delayed recall is performed after 30 minutes, followed by a figure recognition test (Meyers and Meyers, 1995). A total score between 0 and 36 can be obtained for each type of recall (i.e., immediate, delayed, and recognition). A high score indicates better visual memory performance. Scores of immediate recall, delayed recall, and recognition were considered in the analyses.

Pittsburg Sleep Quality Index (PSQI). Sleep disorders were assessed using the PSQI questionnaire (Buysse et al., 1989). The PSQI, widely used in clinical and research settings, has been validated as a screening tool for sleep problems in a mTBI population (Fichtenberg et al., 2001). This self-report questionnaire, which assesses sleep quality, includes 19 items rated on a three-point scale. It measures seven components of sleep perception: sleep quality, sleep latency, sleep duration, usual sleep efficiency, poor daytime sleepiness as well as drowsiness, nocturnal sleep disturbance, and use of a sleep-promoting medication. The overall score, ranging from 0 (i.e., *no difficulty*) to 21 (i.e., *major difficulty*), makes it possible to distinguish between "good" and "poor" sleepers. Subjects with a PSQI greater than five are considered poor sleepers with poor sleep quality.

Multidimensional Fatigue Inventory (MFI). This questionnaire consists of 20 items that measure five components: general fatigue, physical fatigue, mental fatigue, reduced activity, and reduced motivation. Each subscale consists of four questions. The subject is asked to answer each question using a Likert-type scale ranging from 1 (i.e., *strongly disagree*) to 5 (i.e., *strongly agree*; Smets et al., 1995). A total score ranging from 5 to 20 for each dimension of fatigue was analyzed. The higher the score, the greater the level of fatigue. It is important to note that there is no standard for interpreting the total score derived by adding up scores from the subscales. However, sex- and age-specific cut-off scores have been proposed for the *General Fatigue subscale* (Schwarz et al., 2003; Singer et al., 2011).

Rivermead Post-concussion Symptoms Questionnaire (RPQ). The presence and severity of post-concussive symptoms were assessed using the RPQ questionnaire (King et al., 1995). This questionnaire has been validated with individuals who have had mTBI (Medvedev et al., 2018). The RPQ consists of 16 symptoms that assess three categories: somatic complaints, cognitive complaints, and affective complaints (Smith-Seemiller et al., 2003). Patients were asked to compare their status to their pre-accident status. For the present study, three symptoms were assessed: fatigue, sleep disturbance, and memory. Symptoms were evaluated on four points ranging from 0 (i.e., *not at all experienced*) to 4 (i.e., *important symptom*). Scores of 1 (i.e., *symptom present before the accident and unchanged since*) have been excluded from the score calculation as they represent premorbid symptoms.

Statistical analyses. All statistical tests of the hypothesis were carried out at a level of significance of 0.05. All analyses were performed using IBM SPSS statistics 24.0. Descriptive data are presented (i.e., mean, percentage, and standard deviation). For

categorical variables, counts and percentages were reported. The groups were compared on the variables age and educational level using *t* test for normally distributed scores and using Mann-Whitney's *U* test of independent samples for non-parametric performances. The groups were compared on the variable sex using a chi square.

Parametric (i.e., one-factor ANOVA) and non-parametric (i.e., Mann-Whitney's *U*) test analyses were performed to determine whether there was a significant difference between the mTBI and control groups for the different recall trials, immediate recall, delayed recall, and recognition.

Verbal and visual memory tests, standard scores (*z*-test result) of mTBI patients were also analyzed. The percentage of patients with two standard deviations or more was also reported.

As mentioned in the previous section, three symptoms of PCS were the subject of our study: memory, fatigue, and sleep. Three questionnaires were used: RPQ, MFI, and PSQI. Descriptive data from the RPQ questionnaire are presented in percentage. We thus proceeded to objectify the severity of the symptoms reported by patients with a one-sample *t*-test. We then compared the average intensity of the symptom reported by patients to zero (i.e., no symptoms). For MFI questionnaire, we analyzed the five subscales separately. We also compared mTBI patients' general fatigue scores to the threshold score that suggests the presence of significant generalized fatigue (Schwarz et al., 2003; Singer et al., 2011). For the PSQI questionnaire, we compared mTBI scores to the threshold score. Subjects with a PSQI greater than or equal to five are considered to have poor sleep quality. We also compared the average of mTBI patients' scores to the threshold with a student *t*-test for independent samples.

For our third objective, which is exploratory in nature, simple linear regressions were performed to test whether the intensity of memory difficulties, level of fatigue, and sleep quality are predictors of memory performance in the delayed recall conditions.

Results

Participants

In this study, 55 participants, including 25 patients with mTBI (i.e., 10 men, 15 women, aged 20 to 61 years) and 30 control participants (i.e., 12 men and 18 women aged 20 to 64 years) were included. Both groups were matched for age and education (cf. Table 1). We performed a parametric test for independent samples, $t(53) = 0.51$, $p = .62$, and no significant difference was found in age between the two groups. Nevertheless, in terms of education, we conducted a

Table 1

Mean and standard deviation for age and education in mTBI and control groups

Variables	Group	N	M	SD
Age	mTBI	25	38.92	12.02
	Control	30	37.30	11.66
Education	mTBI	24	17.71	3.69
	Control	30	17.37	2.33

Note. One missing data point for education in the mTBI group; M = mean; SD = standard deviation.

non-parametric test (Mann-Whitney's U -test of independent samples, $p = .99$) which indicated that the participants in the two groups did not differ significantly concerning their education levels. Finally, the groups did not differ with respect to their sex, $\chi^2(2, N = 55) = 2.6, p = .39$.

Analyses of differences between mTBI and control groups

Verbal memory using RAVLT. To compare the performance between the mTBI and control groups, only the data from the first recall of the RAVLT met the conditions for the application of a parametric test: a normal distribution, $\bar{W} = 0.97, p = .15$, as well as homogeneity of the variance, $F(1, 55) = 0.01, p = .93$. Therefore, we performed a one-factor ANOVA. For the other variables (i.e., R2, R3, R4, R5, IR, DR, and Rec), we carried out non-parametric tests (i.e., Mann Whitney's U).

The means and standard deviations for each group on the RAVLT test are shown in Table 2. As shown in Table 1, no significant group differences were found on the RAVLT for immediate recall, $U = 675, p = .67$, delayed recall, $U = 647, p = .36$, or recognition, $U = 680.5, p = .71$.

Table 2

Means and standard deviation of RAVLT scores for immediate recall, delayed recall, and recognition for the mTBI and control groups

	RAVLT.IR	RAVLT.DR	RAVLT.Rec
mTBI	$M = 11.22$	$M = 11.31$	$M = 14.28$
	$SD = 2.84$	$SD = 2.44$	$SD = 1.05$
Controls	$M = 11.80$	$M = 11.87$	$M = 14.43$
	$SD = 1.83$	$SD = 1.57$	$SD = 0.82$

Note. DR = delayed recall; IR = immediate recall; M = mean; Rec = recognition; SD = standard deviation.

Table 3

Means and standard deviation of RAVLT scores in the learning phase for the mTBI group and control group

	R1	R2	R3	R4	R5
mTBI	$M = 6.8$	$M = 10.12$	$M = 11.68$	$M = 12.64$	$M = 13.10$
	$SD = 1.8$	$SD = 2.11$	$SD = 1.60$	$SD = 1.50$	$SD = 1.60$
Control	$M = 8.83$	$M = 10.63$	$M = 11.67$	$M = 12.60$	$M = 13.20$
	$SD = 1.74$	$SD = 1.83$	$SD = 1.67$	$SD = 1.50$	$SD = 1.30$

Note. M = mean; R = Recall; SD = standard deviation.

Learning curve. The means and standard deviations are shown in Table 3. The results of these analyses showed a main effect of group for the first recall (i.e., R1), $F(1, 55) = 17.36, p < .001$. As shown in Table 2, the mTBI group had on average a lower scores, $M = 6.8, SD = 1.87$, than the control group, $M = 8.83, SD = 1.74$. On the other hand, no significant difference was found between the two groups for R2, $U = 661.5, p = .51$, R3, $U = 698, p = .97$, R4, $U = 838.5, p = .98$, or R5, $U = 687.5, p = .83$.

Visual memory using ROCF. The means and standard deviations are shown in Table 4. As shown in Table 3, no significant difference was found between the two groups for immediate recall, $U = 634, p = .26$, delayed recall, $U = 663.5, p = .54$, or recognition, $U = 628.5, p = .58$.

Table 4

Means and standard deviation of ROCF scores in the learning phase of the mTBI group and control group

	ROCF.IR	ROCF.DR	ROCF.Rec
mTBI	$M = 19.64$	$M = 19.82$	$M = 20.58$
	$SD = 6.49$	$SD = 6.35$	$SD = 2.43$
Controls	$M = 21.45$	$M = 20.77$	$M = 21.03$
	$SD = 4.37$	$SD = 4.70$	$SD = 1.88$

Note. DR = delayed recall; IR = immediate recall; M = mean; Rec = Recognition; SD = standard deviation.

Despite the absence of a significant difference on average between the performance of the mTBI group and the control group, 20% of patients with mTBI demonstrated a deficit of two standard deviations or more in delayed recall (z -score of mTBI patients) in the visual modality, evaluated with the ROCF. In the verbal modality, evaluated with the RAVLT, all patients with mTBI performed within the norm on delayed recall. The z -score of observation is the number of standard deviations above or below the healthy population mean. A score above two standard deviations is considered deficient.

Post-concussive symptoms. To objectify the severity of the symptoms reported by mTBI patients. We compared the average of the symptoms (i.e., memory, fatigue, and sleep) reported with RPQ to zero (i.e., no symptoms), using one sample t -test. The one-sample t -test, also known as the one-means t -test, is used to compare the mean of a sample to a known (or theoretical/hypothetical) standard mean. In this case, the healthy population is theoretically

Table 5
Means and standard deviation on the MFI, PSQI, and PQP questionnaires

Variable	<i>N</i>	<i>M</i>	<i>SD</i>
MFI general fatigue	24	15.46	3.20
MFI physical fatigue	24	13.96	3.86
MFI mental fatigue	24	15.46	2.69
MFI activation	24	13.83	3.33
MFI motivation	24	10.21	2.55
PSQI	24	8.08	3.53
RPQ sleep	24	2.08	0.26
RPQ fatigue	24	3.00	0.19
RPQ memory	24	2.50	0.16

Note. *M* = mean; *SD* = standard deviation.

expected to have a score of zero, and therefore no PCS.

A significant number of mTBI patients reported PCS. The means and standard deviations are shown in Table 5. We looked at the RPQ questionnaire. In terms of memory difficulties caused by mTBI, 54% of patients reported moderate to severe symptoms. Moderate to severe fatigue was reported by 79% of patients, and 38% reported moderate to severe sleep problems. Results show that complaints of memory difficulties, $M = 2.50$, $SD = 0.16$, for patients with mTBI were significant, $t(24) = 7.96$, $p < .001$. This means that despite the absence of a significant group difference in memory performance between the mTBI group and the control group, mTBI patients still demonstrated significant memory complaints. Similarly, feelings of fatigue were significant, $t(24) = 15.76$, $p < .001$, as were sleep disturbances complaints, $t(24) = 15.70$, $p < .001$.

MFI general fatigue was also analyzed and means are shown in Table 7. Results show that mTBI patients have a significantly higher level of general fatigue than people of their age and gender.

Table 7
Averages of general fatigue, by age and gender

Gender	Age		
	≤ 39 ans	40- 59 ans	≥ 60 ans
Male	13,6 (≥ 9)	16,2 (≥ 11)	-
Female	15,57 (≥ 11)	15,83 (≥ 12)	18 (≥ 14)

Note. Cut-off scores score suggesting the presence of significant general fatigue is shown in parentheses.

For the PSQI questionnaire, a total of 68% of patients showed sleep disturbances relative to the threshold. Results show that mTBI patients, $M = 8.08$, $SD = 3.53$, had significant sleep difficulties, $t(24) = 4.29$, $p < .001$.

Table 6
Results of the simple regression model predicting the delayed recall score of the ROCF test

	<i>B</i>	<i>SE</i>	β	<i>t</i>	<i>p</i>	<i>F</i>	<i>R</i>	<i>R</i> ²
MFI general Fatigue	0.75	0.88	0.18	0.86	.40	0.74	.18	.03
MFI physical fatigue	-0.56	0.73	-0.16	-0.76	.50	0.57	.16	.03
MFI mental fatigue	0.52	1.06	0.10	0.49	.63	0.24	.10	.01
MFI activation	0.42	0.86	0.10	0.49	.63	0.24	.10	.01
MFI motivation	-0.64	1.12	-0.12	-0.57	.57	0.33	.12	.02
PSQI	0.44	0.81	0.12	0.54	.60	0.30	.12	.01
RPQ sleep	3.21	2.13	0.31	1.51	.15	2.28	.31	.09
RPQ fatigue	0.35	3.07	0.02	0.11	.91	0.01	.02	.001
RPQ memory	4.32	3.56	0.25	1.12	.24	1.48	.25	.06

Note. *B* = the intercept; *SE* = Standard Error; β = slope; *t* = *t*-test statistic; *p* = probability value; *F* = *F* statistics; *R* = correlation coefficient; *R*² = coefficient of determination.

Table 7

Results of the simple regression model predicting the delayed recall score of the RAVLT

	<i>B</i>	<i>SE</i>	β	<i>t</i>	<i>p</i>	<i>F</i>	<i>R</i>	<i>R</i> ²
MFI								
general Fatigue	0.06	0.06	0.22	0.97	.34	0.94	.22	.05
MFI								
physical fatigue	0.03	0.05	0.12	0.52	.61	0.27	.12	.01
MFI								
mental fatigue	-0.05	0.07	-0.14	-0.62	.54	0.39	.14	.02
MFI activation	0.10	0.06	0.37	1.72	.10	2.96	.37	.14
MFI motivation	0.01	0.07	0.04	0.19	.85	0.04	.04	.002
PSQI	-0.01	0.05	-0.05	-0.20	.84	0.04	.05	.002
RPQ sleep	0.03	0.14	0.05	0.21	.83	0.05	.05	.002
RPQ fatigue	0.06	0.19	0.07	0.32	.75	1.15	.07	.01
RPQ memory	0.26	0.21	0.27	1.23	.23	1.52	.27	.07

Note. Note. *B* = the intercept; *SE* = Standard Error; β = slope; *t* = *t*-test statistic; *p* = probability value; *F* = *F* statistics; *R* = correlation coefficient; *R*² = coefficient of determination.

Predictive analyses of memory performance.

The results are presented in Tables 6 and Table 7. Analysis of these results shows that the relationship between the complaint of memory difficulties reported by the RPQ and the EM performance assessed by the delayed recalls of the RAVLT and ROCF tests is not significant. Similarly, the intensity of symptoms of fatigue and sleep disorders reported by the RPQ questionnaire, the level and type of fatigue according to the MFI questionnaire, and the quality of sleep measured by the PSQI score do not predict the variables of interest.

Discussion

This study aimed to determine the impact of mTBI on EM in the first few months following the accident and its relationship with PCS. The first objective was to compare the EM performance in the visual and verbal modalities between a mTBI group and a healthy control group. Our findings showed no difference between groups, both in verbal and visual EM. The second objective was to assess memory, fatigue, and sleep complaints of patients who have undergone mTBI. The results have shown that mTBI patients report significantly more memory, fatigue, and sleep complaints in their everyday functioning than a theoretically mean of no PCS complaints in a healthy population. Finally, the third objective of the study was to explore the relationship between memory performances and PCS complaints. In the present study, despite memory complaints, fatigue, and sleep disturbance due to the mTBI, no associations were found between PCS and memory performances formally assessed with objective neuropsychological tests.

Memory profile of patients with acute mTBI

Verbal memory. In the learning phase, no significant differences were found between the two groups, except in the first recall trial. This group effect, found only in the first recall trial, could be explained by the attentional difficulties in the mTBI group. Several studies have shown a decrease in attentional abilities and impaired executive function following TBI at all levels of severity (Dikmen et al., 2009; Kathryn et al., 2011; Truchon et al., 2018). More specifically, relationships have also been observed between executive functions and EM, a study done by Diesfeldt (2006) has shown a strong association between performance on an executive functioning task and the one obtained in an EM task.

In the recall phase, no significant differences were found between the control and mTBI groups in either immediate recall, delayed recall, or recognition. That contrasts with the study by Taiym and colleagues (2016), where mTBI patients showed lower performance in verbal memory than the control group. However, in their study, they used the second version of the *California Verbal Learning Test* which places greater demands on executive functions (categories organization) and is, therefore, more sensitive to assessing the impact of mTBI on memory performance. In addition, their mTBI patients were older than the control group and reported symptoms of depression, and the control group had a higher level of intellectual functioning. In sum, their two groups were not comparables in terms of demographic and individual characteristics.

Visual memory. In the visual modality, results do not show a significant difference between the two in

immediate recall, delayed recall, or recognition. These results contrast with those of the study by L'Écuyer-Giguère et al. (2019) who showed a group difference in both recall conditions. Several hypotheses can be made regarding this discrepancy in results. In their study, both groups were not matched on age, and patients who underwent mTBI were significantly older than the control group (L'Écuyer-Giguère et al., 2019). However, memory is one of the skills most affected by age (Ballesteros et al., 2009; Wammes et al., 2017). In addition, the sample included a higher percentage of complicated mTBI patients (i.e., positive CT-Scan). The present study sample is composed of 96% uncomplicated mTBI and only 4% complicated mTBI. These factors may impact visual memory abilities. Indeed, a complicated mTBI may result in greater cognitive impairment (Dikmen et al., 2017; Borgaro et al., 2003).

Nevertheless, despite the absence of difference in means between the two groups, it is important to mention that a total of 20% of mTBI patients showed clinical impairment in the visual memory test, who was therefore performing beyond two standard deviations from the healthy population mean. In that sense, the absence of a significant difference between the means of the two groups does not necessarily reflect an absence of impairment in the experimental group because the averages do not consider individual differences (Levine, 2002; Kathryn et al., 2011; Wammes et al., 2017; Wilde et al., 2008). In our study, this impaired group is the one at risk of developing long-term sequelae if not managed in the acute phase (Dikmen et al., 2010; Frenchman et al., 2005; Perlstein et al., 2004). From a clinical point of view, it is important to detect patients with cognitive deficits as early as possible to intervene quickly and provide the required cognitive rehabilitation services. Early appropriate interventions may prevent chronic impairment in everyday activities (Dikmen et al., 2017).

Interestingly, in the verbal modality, all mTBI patients performed within the norm. It leads us to ask if TBI has a greater impact on incidental memory, which is more reflective of everyday memory. Indeed, the learning paradigm of the RAVLT is intentional and the subject is involved in the task while it is not the case in the ROCF. There is an interaction between the participant and the experimenter that could potentially increase attentional and concentration abilities, and thus improve memory performance. It is also possible to hypothesize that the visual memory task involves a higher level of executive functions, especially in the organization, planning, and incidental processes of the reproduction of the figure. As noted above, executive functions are frequently affected following mTBI. The word list learning task may be

less affected since it requires less involvement of higher executive functions. It could explain why their scores are within the norm, but they still complain of memory problems. An interesting avenue for research would be to assess whether this form of brain trauma would have a greater impact on visual memory than verbal memory or whether it is incidental memory that is impaired.

Overall, the absence of a difference in memory performance, in the verbal, and visual modalities, between the two groups does not validate our first experimental hypothesis. Given that memory complaints are often reported by patients following mTBI, we expected to find weaker performance than in the control group (Dikmen et al., 2017; Gaines et al., 2015; l'Écuyer-Giguère et al., 2019; Tayim et al., 2016). On the other hand, the results of this study are consistent with neuroimaging studies, which have concluded that no significant difference was found between TBI patients and the control group, at the behavioral level, and showed a significant difference between the two groups in terms of brain activation (Kathryn et al., 2011; Levine, 2002). It is important to note that these different studies (Kathryn et al., 2011; Levine, 2002) were conducted on patients with any severity of TBI. It is possible that at a cerebral level there is an impairment, not detectable with neuropsychological tests and basic imaging techniques, which could explain the memory complaints evoked by patients. Thus, it would be interesting in future studies to further investigate and characterize the neural substrates of EM following mTBI to better understand the impact of this type of injury on memory capacity.

Post-concussive symptoms following mTBI

When the neuropsychological assessment of a patient who has undergone mTBI is within the norm, self-reported complaints may be central to differentiating PCS from psychiatric problems (Sigurdardottir et al., 2009; Wayne et al., 2000). Therefore, the second objective was to objectify the subjective complaint by comparing it to the threshold score.

Memory. Neuropsychological tests assess memory difficulties. However, it is important to note that learning and recalling a complex word list or figure in an evaluative context may not reflect the memory difficulties that the individual faces in everyday functioning. Hence the need to consider the intensity of self-reported complaints even if the self-assessment of impairments may have some limits. For example, patients may have tendencies to exaggerate or minimize their problems. In this study, memory difficulties generated by mTBI, as assessed by the RPQ, were significant. More than half of the

participants reported moderate to significant memory difficulties when comparing their current state to their pre-accident state. Because of the limitations of self-report, it is important to note that our patient cohort was not in a litigation setting, so it is possible to assume that these patients did not exaggerate their memory complaints to obtain a secondary gain. Memory difficulties could manifest themselves as difficulties in learning new information or remembering a personally experienced event. This decrease in efficiency disrupts the return to work or school and disrupts an individual's daily functioning in managing simple to complex tasks (Dikmen et al., 2010; Carroll et al., 2004; Carroll et al., 2014).

Fatigue. Post-mTBI fatigue is often reported by patients (Johansson & Rönnbäck, 2017; Ponsford et al., 2019; Schiehser et al., 2016; Stullemeijer et al., 2006; Wylie & Flashman, 2017). Fatigue was also reported and objectified with the RPQ and MFI questionnaires by participants in our study. According to the RPQ, 79% of the participants suffer from moderate to severe fatigue following mTBI. Similarly, according to the results from the MFI questionnaire, mTBI patients have a higher level of general fatigue than people of their age and sex. Indeed, following mTBI, subjects are required to use additional cognitive resources. This increased mental effort leads to cognitive fatigue. On the other hand, fatigue may result from other factors, such as the quality of sleep (Wylie & Flashman, 2017), which would accentuate memory difficulties. It would be interesting to determine whether fatigue is a cause or a consequence of memory difficulties and work on this link to improve memory performance and, thus, the patients' quality of life.

Sleep. According to the PSQI score, 68% of mTBI patients have poor sleep quality. Also, as revealed by the RPQ, 38% reported moderate to severe sleep disturbance following injury. Several studies support those results because they have demonstrated altered sleep quality following mTBI (Cassidy et al., 2014; Ponsford & Sinclair, 2014; Viola-Saltzman & Musleh, 2016; Wylie & Flashman, 2017). Sleep plays a crucial role in consolidating information learned during the day (Gais, 2006), which may explain the memory difficulties faced by people with mTBI. It is therefore pertinent to take sleep quality into account when interpreting memory performance. Similarly, it could be beneficial to address alterations in the sleep-wake cycle, which may interfere with recovery and resumption of daily activities (Wylie & Flashman, 2017). Various studies have highlighted the importance of pharmacological and non-pharmacological interventions and their positive impacts on sleep quality and fatigue (Ponsford et al., 2012; Ponsford & Sinclair, 2014; Wylie & Flashman, 2017).

Influence of PCS on memory performance. The third objective of the study was to explore the relationship between a subjective complaint and memory performance and to study the influence of fatigue and sleep on the variables of interest. Results reveal that the relationship between self-reported memory difficulties and memory performance, as assessed by neuropsychological tests, is non-significant. It means that the RAVLT and FCR tests do not make it possible to objectify the difficulties generated by an mTBI that patients must face in their everyday life. An example could be encoding new information into EM, especially when the attention of dual-task is demanding (Mangels, 2002). Similarly, the level of fatigue and sleep quality does not predict memory performance.

In many studies, the impact of mTBI on memory is concluded without considering the intensity of PCS. Yet, the presence of a complaint of memory abilities, a significant level of fatigue, and poor sleep quality, is often reported by patients who have undergone a TBI (Cassidy et al., 2014; Dikmen and 2010). These PCSs impact patients' daily functioning on various levels (e.g., return to work, return to school, social reintegration) (Bier et al., 2009; Cassidy et al., 2004; Johansson et al., 2016; Wylie & Flashman, 2017). Our study provides a novel and critical element in a clinical assessment, namely, to see the relationship between patient-reported PCS and the neuropsychological tests most used in the clinic to assess memory abilities.

In our study, we couldn't establish a link between post-concussive symptoms and memory performance in visual or verbal modalities. None of the PCSs, assessed by RPQ, MFI, and PSQI, predicted the verbal memory score, assessed by the RAVLT, or the visual memory score, assessed by the ROCF test. Bearing in mind that the assessment was performed in the first weeks after the accident, in the acute phase, when PCS is still important. To conclude, the complaints reported by the patients having undergone a mTBI are indeed present and significant, and yet we do not find an association between memory performance and the intensity of these PCS. Thus, it is crucial to consider the patient when choosing tests. These findings call into question the sensitivity of neuropsychological tests to measure the subtleties of memory impairment following mTBI and perhaps also the lack of ecological validity of these measures for most patients. Researchers are therefore encouraged to develop more sensitive memory tests for this clinical population. However, one of the issues that emerge is the need for a formal assessment for all patients. Thus, instead of systematically assessing all patients with mTBI, conduct more targeted assessments but initiate management based on patient complaints and not only on objective test difficulties.

Limitations of the study

Notwithstanding the relevant findings revealed in this study, several limitations have already been mentioned. Firstly, the number of participants is small, and we use non-parametric tests to compare the memory performance of mTBI patients and the control group. It is important to note that the statistical power of non-parametric tests is low. Although both groups were matched in age and education, the participant's age varies between 20 and 64. Since we compared the raw score to compare the two groups, the age variable could explain the heterogeneity of the data. Similarly, it is essential to control for the intelligence quotient, as the latter could play a role in memory performance (Ashton et al., 2005; L'Écuyer-Giguère et al., 2019) and could thus explain the good performance of the experimental group despite their mTBI.

As for the evaluation of PCS, measures used came from self-reported questionnaires and it may not be sensitive enough to measure complex and subtler symptoms. Complaints are considered subjective. Thus, the psychological aspect must be considered, in the sense that experiencing a negative event, which could be traumatic for some people, may lead to an underestimation of current abilities and an impression that the pre-accident status was better than it was (Iverson et al., 2010). Iverson and colleagues (2010) have shown that patients with mTBI have a "good old days" bias, impacting their perception of their difficulty, recovery, return to work, and resumption of daily activities. In this sense, the present study did not explore the impact of anxiety or depression, which may influence fatigue levels. People in an anxious state also feel much more fatigued, presumably because they are expending so much mental effort on their anxious state that they become fatigued.

Clinical perspectives

This study's results underscore the importance of developing new, more ecologically valid tests that allow for the objectification of complaints reported by patients. Rabin et al. (2016) conducted a longitudinal study to examine the use of neuropsychological tests used in Canada and the United States, which included RAVLT and ROCF. Their results revealed a high degree of stability in the tests used over the past ten years. Most clinical neuropsychologists continue to use the same tests as they become more comfortable scoring and interpreting the data, although they are aware that in some cases the tests do not assess the difficulties reported by patients. The use of new instruments is a real challenge in clinical practice. Nevertheless, it is crucial to develop new, more ecologically valid tests that consider the different influencing variables (e.g., PCS). Objectifying difficulties in the acute phase with a more sensitive

examination makes it possible to guide management and reduce the risk of developing chronic sequelae. In this context, it is therefore essential to interpret the results obtained with great caution.

Conclusion

The literature review led us to hypothesize that memory difficulties in patients who have undergone mTBI and the presence of PCS may play a role in predicting memory performance. However, the results of the present study evaluated with the ROCF test between patients with mTBI and the control group are not significant. Despite the presence of a significant memory complaint, the latter is not revealed with the neuropsychological tests most used in the clinic. As for PCS, fatigue, and sleep are significant. However, it appears that they do not predict memory performance. This underscores the importance of paying attention to self-reported subjective information in the interpretation of the data, to address the difficulties that patients face in their daily lives. Finally, further research with larger groups is essential to better understand the impacts of mTBI on EM and the influence of PCS on this cognitive process.

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