THE IMPACTS OF MILD TRAUMATIC BRAIN INJURY ON CENTRAL AUDITORY PROCESSING IN SCHOOL-AGED CHILDREN

FAUVE DUQUETTE-LAPLANTE

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Faculty of Health Sciences
University of Ottawa

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Presented by
Fauve Duquette-Laplante

Evaluated by a jury composed of the following:

Éric Doucet
Président-rapporteur

Amineh Koravand
Research supervisor at the University of Ottawa

Benoît Jutras
Codirecteur de recherche à l'Université de Montréal

Shanna Kousaie
Internal Examiner (University of Ottawa)

Karine Marcotte
Membre du jury (Université de Montréal)

Anna Zumbansen
Internal Examiner (University of Ottawa)

Natacha Trudeau
Membre du jury (Université de Montréal)

Deborah Moncrieff
External Examiner

ABSTRACT

The prevalence of mild traumatic brain injury (mTBI) among children has risen significantly in recent years. However, literature on hearing difficulties in children with mTBI, regardless of severity, remains scarce. Existing studies suggest that auditory processing, particularly in noisy environments like classrooms, may be impaired in these children, potentially leading to inattention behaviours post-injury. The current PhD project aimed to assess central auditory processing and listening behaviours in school-aged children with mTBI. Specifically, the project sought to (1) document functional and impaired auditory processing in this group, (2) explore children's and parents' perceptions of listening behaviours, (3) identify neurophysiological markers of auditory dysfunction post-mTBI, (4) and see if the results change over time. To answer these aims, a prospective cohort study with comparison was conducted. It was composed of two experiments: a behavioural experiment with central auditory behavioural tests, cognitive screenings, and questionnaires (self-reported and parental), and a second experiment with auditory evoked potentials in quiet and in noise with a preliminary study to establish optimal parameters for electrophysiological measurements in noise. Both experiments were carried out twice: Time 1 – shortly after mTBI diagnosis or following recruitment for controls and Time 2 – three months later to monitor symptom persistence or emergence. The findings of behavioural auditory tests revealed significant auditory impairments in temporal processing in a subset of children with a mTBI, while no neurophysiological biomarkers of mTBI could be identified in quiet or in noise. This knowledge could inform auditory evaluations following mTBI and, in turn, interventions to mitigate mTBI's impact on communication in school settings and guide post-injury rehabilitation strategies, potentially assessing recovery over time.

Keywords: Audiology, mild traumatic brain injury, mTBI, auditory processing, EEG, pediatrics

RÉSUMÉ

La prévalence du traumatisme crâniocérébral léger (TCC-L) chez les enfants a significativement augmenté ces dernières années. Cependant, la littérature répertoriant leurs difficultés auditives, indépendamment de la gravité, reste rare. Les études suggèrent que le traitement auditif, notamment dans des environnements bruyants comme les salles de classe, peut être altéré chez ces enfants, ce qui pourrait entraîner des comportements d'inattention après le trauma. Ce projet de doctorat visait à évaluer le traitement auditif central et les comportements d'écoute chez les enfants d'âge scolaire atteints de TCC-L. Plus précisément, les objectifs étaient de (1) documenter le traitement auditif fonctionnel et altéré dans ce groupe, (2) explorer les perceptions des enfants et des parents concernant les comportements d'écoute, et (3) identifier un ou des marqueurs neurophysiologiques associés au TCC-L (4) documenter les changements dans le temps. Pour répondre à ces objectifs, une étude prospective de cohorte avec comparaison a été menée. Elle était composée de deux expérimentations : une expérimentation comportementale avec des tests auditifs centraux, un dépistage cognitif et des questionnaires (enfants et parentaux), et une deuxième expérimentation mesurant des potentiels évoqués auditifs dans le silence et dans le bruit. Cette dernière expérimentation a été précédée par la collecte de données préliminaires pour établir les paramètres optimaux pour les mesures électrophysiologiques dans le bruit. Les deux expérimentations ont été réalisées à deux reprises : au Temps 1 - peu de temps après le diagnostic de TCC-L ou suivant le recrutement pour le groupe contrôle et Temps 2 - trois mois plus tard pour surveiller la persistance ou l'émergence des symptômes. Les résultats des tests comportementaux ont révélé des incapacités auditives significatives reliées au traitement temporel chez un sous-groupe d'enfants ayant un TCC-L, tandis qu'aucun biomarqueur neurophysiologique n'a pu être identifié dans le silence ou dans le bruit. Ces connaissances pourraient améliorer l’évaluation auditive après un TCC-L et, par conséquent, les interventions pour atténuer l'impact du TCC-L sur la communication dans les milieux scolaires. À terme, ces connaissances permettront l’orientation des stratégies de réadaptation post-trauma, en évaluant le potentiel de récupération au fil du temps.

Mots-clés : audiologie, traumatisme crâniocérébral léger, TCC-L, traitement auditif, EEG, pédiatrie

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ACRONYMS AND ABBREVIATION LIST

ABRs: auditory brainstem responses

ADHD: Attention deficits hyperactivity disorder

AEPs: auditory evoked potentials

Ag/AgCl: Silver chloride

ALRs: auditory late responses

AMRs: auditory middle responses

ANOVA: Analysis of Variance

APD: Auditory Processing Disorders

CHUSJ: Centre Hospitalier Universitaire Sainte Justine

CNSVS: Central Nervous System Vital Signs

CUSM: Centre Universitaire Santé de Montréal

dB: decibels

dBA: decibels A

DPT: duration pattern test

EDC: écoute dichotique de chiffres

EEG: electroencephalogram

FC: functional connectivity

GIN: gaps in noise

Hz: Hertz

ITPC: Intertrial phase clustering

kΩ: Kiloohms

MLD: masking level difference

mTBI: mild Traumatic Brain Injury

µV: microvolts

msec or ms: milliseconds

PCSI: Postconcussion symptom inventory

PPST: pitch pattern sequence test

RMANOVA: Repeated measures Analysis of Variance

SAB: Scale of auditory behaviours

SL: sensation level

SNR: signal-to-noise ratio

SPL: Sound pressure level

T1: Time 1

T2: Time 2

TBI: Traumatic Brain Injury

TCC-L : Traumatisme crâniocérébral léger

TFA: Time-frequency analysis

TMB: tests de mots dans le bruit

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À ma famille et Marc-André

THESIS ORGANIZATION

The current thesis is composed of five chapters. The first chapter encompasses the introduction, which presents the rationale and literature surrounding the subject of the thesis as well as the objectives, hypothesis and experiment organization and methodology. The second chapter is devoted to an experiment in which children with mild traumatic brain injury (mTBI) were assessed using central behavioural auditory tests, a cognitive screening test and questionnaires. The third chapter contains three articles related to the electrophysiological evaluation of children with mTBI. The two initial articles relate to a preliminary experiment designed to select the parameters of the electrophysiological measures for the third experiment. This experiment led to the writing of a third article presented in this chapter. The article focuses on the electrophysiological evaluation of children post-mTBI and their controls. The fourth chapter encapsulates the general discussion based on thesis experiments and the observation of individual data, in addition to issuing recommendations on evaluating children's auditory abilities/functions following an mTBI. It also provides insight into further explorations in research in children with mTBI. Finally, the fifth chapter is a general conclusion.

CHAPTER 1. Introduction

1.1. mild Traumatic Brain Injury (mTBI)

Traumatic brain injury (TBI) is defined as the result of a traumatic event producing a physiological disturbance of the brain (Kay et al., 1993). TBI does not result from a neurodegenerative or neurodevelopmental condition (Kay et al., 1993). Two main mechanisms cause such a physiological disruption in the brain: contact and inertia (McAllister, 2011). Contact refers to the brain's surface colliding with the skull, leading to a contusion injury (Adams et al., 1980; Eierud et al., 2014; Levin et al., 1992), and inertia, to the force of the movement causing impact tears and compression of the brain's tissues, leading to diffuse axonal injury (Büki & Povlishock, 2006; Eierud et al., 2014; Povlishock et al., 1992). The prevalence of traumatic brain injury is estimated at 69 million people affected worldwide (Dewan et al., 2016). In children, the incidence of TBI ranges from 185 (Kraus, 1986) to 865 (Falk et al., 2009) per 100,000 children. Of those TBIs, about 80-90% are classified as mild trauma or mTBI (Hawley et al., 2003; Kraus, 1986; Kuitunen et al., 2023; Quayle et al., 2014). In the literature, mTBI is not the only term utilized to describe a mild form of head trauma. In multiple studies, especially sports-related research, the term concussion is often used interchangeably with mTBI (Keays et al., 2018; McKinlay et al., 2011; Sussman et al., 2018; Voss et al., 2015). For the current literature review and the articles included in this thesis, the term mTBI will be utilized throughout, irrespective of the terminology in the referred and reviewed articles.

mTBI is generally diagnosed according to four main criteria: (1) a score of 13 to 15 on the Glasgow Coma Scale (Teasdale & Jennett, 1974); (2) loss of consciousness lasting no more than 30 minutes; (3) altered state of consciousness for a maximum of 24 hours; (4) post-traumatic amnesia lasting no more than 24 hours (Kay et al., 1993; Truchon et al., 2018). When available brain imaging findings can indicate the presence or absence of focal non-surgical neurological deficit, but mTBI can be diagnosed with or without these findings. (Kay et al., 1993; Truchon et al., 2018).

Negative repercussions following mTBI can range from temporary to permanent, and brain imaging findings do not necessarily correlate with their persistence (Carroll et al., 2014; Hanlon

et al., 1999; Tellier et al., 2009). The persistence of mTBI related difficulties does not occur in all children; nonetheless, multiple studies estimate the proportion of affected children to be between 10% (K. M. Barlow et al., 2010, 2015) and 30% (Babcock et al., 2013). Even with a very conservative estimate of 3 million children worldwide sustaining a mTBI every year (Dewan et al., 2016), there would be approximately an additional 240,000 to 720,000 children suffering from the persistent effects of mTBI yearly. Chronology for mTBI related difficulties follow a timeline from acute to chronic, with their persistence for over three months defined as the chronicity of those difficulties (Cooksley et al., 2018).

Although mTBI is, by definition, classified as the mildest form of TBI, this degree of severity in no way diminishes the fact that it can lead to negative outcomes in the physical, emotional, cognitive or sensory realms (Babcock et al., 2013; Lumba-Brown et al., 2018; Nowacki et al., 2017; Reed et al., 2022). The most documented symptoms and impairments in children are headaches, cognitive impairment in attention, memory, learning, reaction time or executive functioning, vestibulo-oculomotor dysfunction and sleep difficulties (Lumba-Brown et al., 2018). Other symptoms frequently reported by children following an mTBI are fatigue, balance problems, nausea, dizziness, and sensitivity to light and noise (Lyons et al., 2022). Emotional symptoms such as anxiety and depression have also been reported (Macartney et al., 2021). The most documented symptoms and impairments, such as post-traumatic headaches or cognitive impairment, are well-researched and well-described and are integral parts of the diagnosis and rehabilitation guidelines following a mTBI (Lumba-Brown et al., 2018; Reed et al., 2022).

Regarding sensory implications, studies have mostly documented vision and balance-related sensory symptoms or impairments (Lumba-Brown et al., 2018; Lyons et al., 2022; Master et al., 2016; Phillipou et al., 2014). Most mTBI clinical guidelines contain diagnostic criteria and rehabilitation plans for vision and balance disorders (Lumba-Brown et al., 2018; Reed et al., 2022). Auditory symptoms and impairment, when investigated, are often reported in adults (Gosselin et al., 2006; Hoover et al., 2017; Knoll et al., 2020; Krizman et al., 2023; Vander Werff, 2012; Vander Werff & Rieger, 2019a, 2019b). Unfortunately, auditory-related difficulties are often neglected in mTBI management guidelines in both children and adults. As expressed by Theodoroff and collaborators in 2022 in the article “Concussion Management Guidelines Neglect Auditory Symptoms”, the authors underline the need for more research on auditory symptoms and

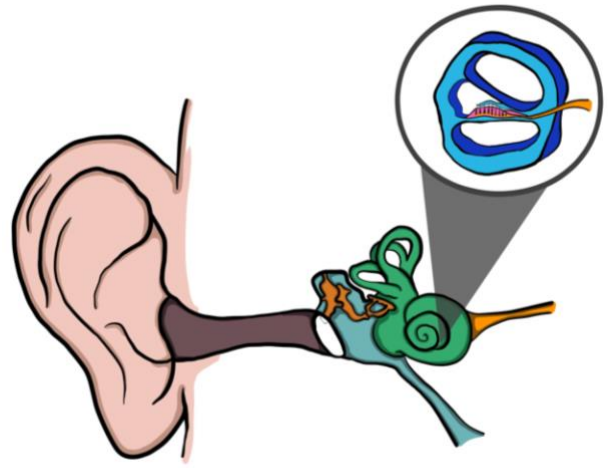
impairments following mTBI and how they are often missed in the diagnosis and, therefore, rehabilitation following a mTBI (Theodoroff et al., 2022).

Literature on this topic is scarce, especially in children. Sensory difficulties at the auditory level in children with TBI, regardless of severity, are poorly documented (Bakker et al., 2014, 2016; Lumba-Brown et al., 2018; Lyons et al., 2022; Master et al., 2016; Phillipou et al., 2014; Schriever et al., 2014). Most TBI studies carried out in the pediatric population often concentrate on moderate to severe TBI, and when they include children with mTBI, they do not discriminate them from other TBI severities (Cockrell & Gregory, 1992; De Godoy et al., 2022; Deutsch & Zawel, 1966; Flood et al., 2005). Therefore, this review included adult-related mTBI literature as well as research with all severities of TBI to represent most of the auditory research conducted with either children or mTBI.

1.2. The auditory system

Where the peripheral auditory system "hears", the central auditory system "understands" (Bellis, 2003). Auditory symptoms and impairments following a mTBI can originate from the peripheral (see Figure 1a) or central (see Figure 1b) auditory systems.

a



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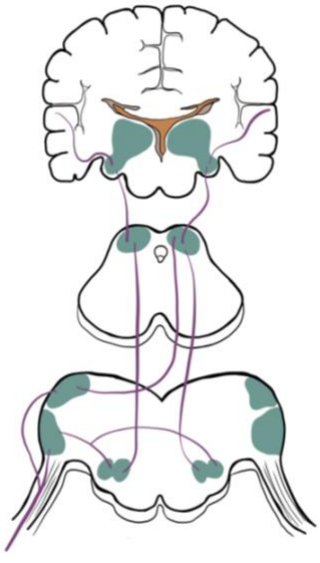

Figure 1. The peripheral (a) and central (b) auditory system.

1.2.1. The peripheral auditory system

The peripheral auditory system basically includes the structures of the outer, middle, and inner ear (Musiek & Baran, 2018) (Figure 2a). The role of the peripheral auditory system is to transform physical soundwaves into neural input. The maturation of the peripheral auditory system is attained at birth (Jutras et al., 2020). Generally, both behavioural and objective tests are employed to measure the peripheral auditory system's function such as otoscopy for the outer ear and immitancemetry for the middle ear and otoacoustic emissions for the inner ear. Audiometry is utilized to measure hearing levels of tonal and speech sound (Jutras et al., 2020).

1.2.2. The central auditory system

The central auditory system encompasses the brainstem and structures of the auditory cortex (Musiek & Baran, 2018) (Figure 1b). The central auditory system processes auditory input associated with auditory abilities, including binaural integration, binaural separation, binaural interaction, temporal processing, auditory closure, and figure-ground separation (Bellis, 2003). The central auditory system's maturation, unlike the peripheral auditory system, is not fully mature in children. While certain auditory abilities attain adult-like performances around age 12, full maturation of the central auditory system does not happen until adulthood (Bellis, 2003; Jutras et al., 2020; Ponton et al., 2000; Sharma et al., 1997). The central auditory system can be assessed with behavioural and electrophysiological measures which have complementary strengths and weaknesses (see Table 1).

1.2.2.1. Behavioural measures

Different behavioural tests have been developed to evaluate each auditory ability (Bellis, 2003). The following examples represented a non-exhaustive list of tests for each ability that have been developed in French or in English, available in Canada. Binaural integration, the ability to integrate information from both ears, is commonly evaluated with the Dichotic digits test (French: Jutras et al., 2012; English: Musiek, 1983) or the Staggered Spondaic Word test (French: Rudmin & Normandin, 1981; English: Katz et al., 1963). In these tests, different numbers or words are presented simultaneously in both ears and must be repeated by the person evaluated. Binaural separation is the ability to attend to auditory information presented in one ear when ignoring the auditory information sent at the same time to the other ear. It is often evaluated with the Competing

Sentences test (English: Willeford & Burleigh, 1994) or the Synthetic Sentence Identification – Contralateral Competing Message (French: Lynch & Normandin, 1983; English: Jerger & Jerger, 1974). Binaural interaction, the ability to lateralize (left, right or central) auditory information presented under earphones, can be evaluated via the Masking Level difference (MLD). For this test, the person must detect a sound among noise when the phase of the sound or the noise can vary (Lynn et al., 1981). Temporal processing, such as temporal ordering, can be assessed, among others, with the Pitch pattern sequence test (PPST) or Duration pattern test (DPT) (Musiek, 1994). The person must repeat series of sequences of three sounds, two of which have the same frequency or duration. Temporal resolution tests are also available to evaluate the ability of a person to perceive the smallest silence interval between two sounds (Random Gap Detection Test: Keith, 2000) or within noise (Gaps In Noise test: Shinn et al., 2009). Auditory closure, the ability to understand speech when either filtered (English: Wilson & Mueller, 1984) or time-compressed (English: Wilson et al., 1994). Figure-ground separation is the ability to understand speech in noise. It can be evaluated with a words-in-noise test (French: Test de Mots dans le Bruit: Lagacé, 2010; English: Word in Noise test: Wilson, 2003), sentences-in-noise tests such as the Synthetic Sentence Identification – Ipsilateral Competing Message (French: Lynch & Normandin, 1983; English: Jerger & Jerger, 1974), the Hearing in noise test (French: Laroche et al., 2006; English: Nilsson et al., 1994) or the Bamford-Kowal-Bench Speech In Noise test (English: Bench et al., 1979)

1.2.2.2. Electrophysiological measures

Specific sensory events trigger a train of action potentials involving the activation of different neurons one after the other in a specific order (Gerstein & Perkel, 1969). Recording these trains of action potentials using electroencephalographic measurements is a way to analyze the temporal relationship between different neuronal regions (Gerstein & Perkel, 1969) and further explore central auditory processing.

1.2.2.2.1. Auditory evoked potentials (AEPs)

AEPs are commonly used to evaluate central auditory processing. They are defined as electrical responses in the brain generated by auditory stimulation (Hall, 1992). Several types of AEPs exist, including but not limited to auditory brainstem responses (ABRs), auditory middle latency responses (AMRs) and auditory late responses (ALRs). Both Vander Werff (2012) and Washnik

et al. (2019) reviewed these types of measures and reported that they would be an option for detecting subtle dysfunctions that may occur in subcortical and cortical structures in people with mTBI. As ALRs help understand how cortical areas of the brain process sounds (Woods et al., 1987), they appear to be particularly appropriate in evaluating the auditory processing in the central auditory system following a mTBI (Vander Werff, 2012).

In adults, ALRs are composed of four-wave components, P1, N1, P2, and N2 (see Figure 2a), where P1 is the first positive wave component appearing between 50 and 80 ms after the onset of auditory stimulation, generated by adjacent areas of the primary auditory cortex (Liégeois-Chauvel et al., 1994). The N1, the first negative wave component, is thought to be generated by the secondary auditory cortex and appears between 80 and 150 ms after auditory stimulation (Vaughan & Ritter, 1970). The P2 wave is the second positive wave component, generally found between 160 and 180 ms after auditory stimulation, also generated by the activity of the secondary auditory cortex (Rif et al., 1991). Finally, the N2 wave, originating from the overall activity of the temporal lobe, is the second negative wave found between 180 and 250 ms after auditory stimulation (Perrault & Picton, 1984). As the auditory system generally attains maturity during adolescence (Ponton et al., 2000; Wunderlich et al., 2006), in children, the ALRs are generally composed of two-wave components (See Figure 2b): P1, appearing between 50 and 150 ms and N2, appearing between 150 and 350 ms (Sharma et al., 1997).

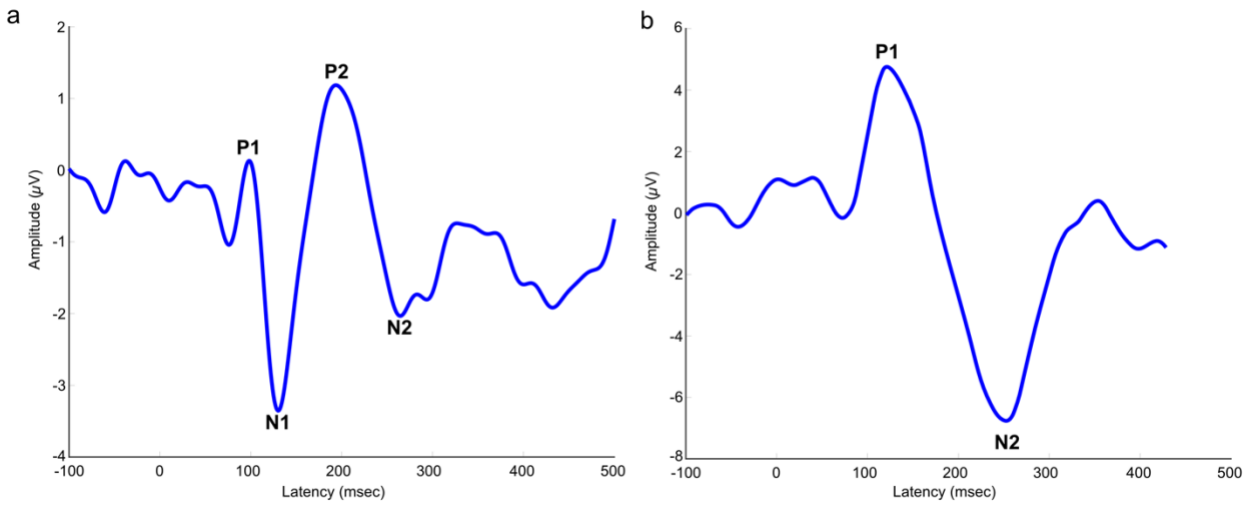

Figure 2. Auditory Late Responses main wave components in adults (a) and children (b).

1.2.2.2.2. Beyond the AEPs

Time-locked responses, such as ALRs, represent only a fraction of what is measured with an electroencephalogram (EEG). Rhythmic voltage changes are observable when studying the brain with an EEG (Varela et al., 2001). These fluctuations, named neural oscillations, are the synchronous and rhythmic electrical activity of the neurones in the brain that are generated spontaneously or from structural or input coupling (Fries, 2005). These neural oscillations operate from low to high frequencies on multiple time scales (Buzsáki & Draguhn, 2004) (Figure 3). Oscillations associated with different frequency bands have been related to different brain functions and states (Wang, 2010). Generally, five main frequency bands are commonly described in the literature (Keil et al., 2022). Delta waves (δ) have a frequency range of 0.5 to 4 Hz. These slow oscillations are often associated with deep sleep, unconsciousness, and abnormal brain states (Gloor et al., 1977). They are prominent in infants during sleep and are often associated with fundamental biological processes and the dopaminergic system level (Jacobs et al., 2007; Knyazev, 2007; Steriade et al., 1993). Theta waves (θ) have a frequency range of 4 to 8 Hz and are observed during drowsiness, early stages of sleep, and in specific cognitive tasks such as planning and reading instructions (Jacobs et al., 2007). They are often associated with memory processes, spatial navigation, emotions, and memory (Kirk & Mackay, 2003; Knyazev, 2007). Alpha waves (α) have a frequency range of 8 to 13 Hz. They are prominent during relaxed wakefulness with closed eyes and are often attenuated when the eyes are open or during active cognitive engagement. Alpha rhythms are commonly associated with wakeful rest, inhibition and cortical information processing (Davidson et al., 1990; Knyazev, 2007). Beta waves (β) have a frequency range of 13 to 30 Hz. They are associated with active, alert, and focused mental activity (Steriade et al., 1993). They are often observed with movement, attention and vigilance during cognitive tasks, problem-solving, and sensory-motor activities (Gola et al., 2012; Wróbel, 2000). Gamma waves (γ) have a frequency range of 30 to 100+ Hz. Considered fast oscillations, these oscillations are associated with cognitive processes, attention, and perceptual binding with object representation (Tallon-Baudry & Bertrand, 1999). They are often involved in higher-order cognitive functions and are thought to be related to conscious awareness (Steriade et al., 1993).

These frequency bands are general categories, and the specific frequencies associated with each band can vary slightly across studies and individuals. Moreover, these bands are not rigidly

defined; they can overlap, and their interpretation may depend on the context of the EEG recording (e.g., during different cognitive tasks, sleep stages, or clinical conditions).

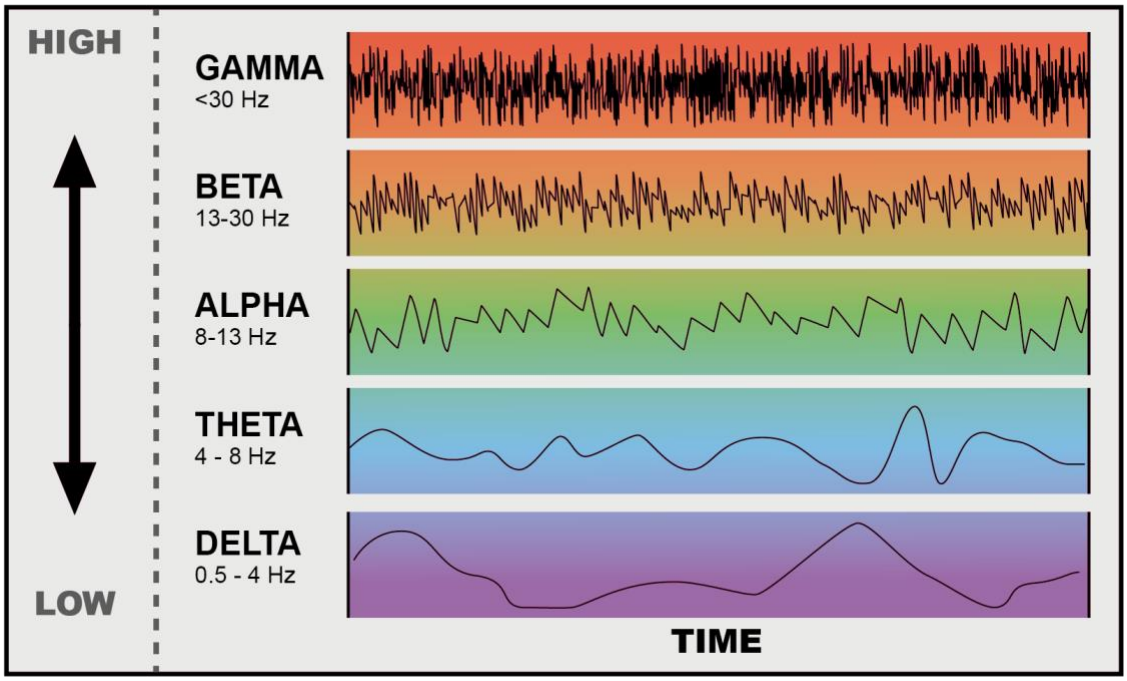

Figure 3. Low to high frequency bands (delta to gamma) of the neural oscillations.

Neural oscillations can generally be separated into the following categories: spontaneous, phase-locked, and non-phase-locked. Spontaneous activity is always present, as there is constant activity in the brain (Freeman, 2004). Phase-locked and non-phase-locked activity, also often referred to as evoked and induced activity, respectively, are present following stimulation or during a task (David et al., 2006). While phase-locked activity can be averaged over the time domain, non-phase-locked activity cannot. However, with other means of analysis, such as single trial time-frequency analysis, it is possible to quantify both evoked and induced activity over the time-frequency domain. Neural oscillations recorded by EEG have four main components: time, frequency, power, and phase. Time-frequency combination allows the analysis of a greater part of the EEG than time-locked evoked potentials and can provide information on how specific stimuli modulate oscillations (Makeig, 1993; Makeig et al., 2004). Phase and power components are independent of each other and are modulated differently by stimuli, which indicates that they provide insights into different aspects of the oscillatory activity (Achimowicz, 1991; Pfurtscheller

& Klimesch, 1991; Van Dijk et al., 1992a). They can be employed together to provide a more comprehensive understanding of the dynamic changes in neural activity (Achimowicz, 1991; Pfurtscheller & Klimesch, 1991; Van Dijk et al., 1992a).

Power refers to the signal's magnitude and voltage amplitude related to the EEG measures (Cohen, 2014; Pfurtscheller & Klimesch, 1991). Power analysis focuses on the amplitude or intensity of different frequency components in the EEG signal. It provides information about the strength of neural oscillations at specific frequencies and how this strength changes over time. Power is generally computed by squaring the magnitude of the signal in each frequency band, and the result is typically expressed in terms of absolute power in microvolts squared (μV^2) or converted to decibels (dB), where it expresses the change in power relative to the baseline (Cohen, 2014). Power analysis can reveal dominant frequency bands associated with different cognitive processes and can be studied in specific brain regions or across the entire scalp (Cohen, 2014; 2017).

Phase analysis examines the timing or phase relationships between different frequency components in the EEG signal (Achimowicz, 1991; Cohen, 2014; Van Dijk et al., 1992b). Intertrial Phase Clustering (ITPC) provides information about the synchronization or coordination of neural activity across different brain regions. The phase of a signal is often represented in radians and can be extracted using multiple techniques (Cohen, 2014). Phase analysis helps identify phase locking patterns or phase coupling between different frequency bands. Phase analysis outputs a coefficient between 0 (no phase coupling) and 1 (complete phase coupling).

Table 1. Behavioural and electrophysiological measures pros and cons

Type of measure	Pros	Cons
Behavioural	• Easy to administer • Age-appropriate normative date • assess auditory abilities	• Can be affected by motivation, fatigue or cognition • Does not indicate the brain area • No norms usually for children younger than 6 years old
Electrophysiological	• Objective • Does not necessarily require participation • No age limitations	• Does not have direct brain to behavioural correlates • Not all measures have normative data • Sensitive to movement and physiological noise

1.3. mTBI and the auditory system

1.3.1. mTBI and the peripheral auditory system

Specific peripheral auditory difficulties related to mTBI in children are rare, but noise sensitivity, hearing loss and tinnitus have been previously reported. When including all severities of TBI, hearing loss (Cockrell & Gregory, 1992; Gettig et al., 2009; Zimmerman et al., 1993), often accompanied by a skull fracture (Gettig et al., 2009; Zimmerman et al., 1993), is a commonly reported impairment. Damage to the hair cells in the cochlea has also been observed without being quantified as hearing loss (Stahl et al., 2024). White et al.'s (2022) retrospective study reported that 54% of the participants, adults and children who had suffered at least one TBI, had cochlea damage as documented by reduced or absent otoacoustic emissions. Tinnitus – perceived sound/s (generally hissing or crackling) not originating from an external source (Jastreboff, 1990; Jastreboff et al., 1988) – is a symptom commonly seen among adults with mTBI (Bergemalm & Borg, 2005; Knoll et al., 2020; Swan et al., 2017). Children with mTBI rarely report tinnitus (Chrisman et al., 2013), which could be explained by a lack of investigation of this symptom or children's inability to understand this concept and questions relating to tinnitus. The most documented symptom is noise sensitivity – being relatively loud or specific sounds perceived as disturbing (Dischinger et al., 2009; Lyons et al., 2022). This auditory symptom is subjectively reported by children with mTBI or their parents using questionnaires such as the *Post-Concussion*

Symptom Inventory (PCSI) (Sady et al., 2014). Utilizing the PCSI, Lyons et al. (2022) revealed that 13.5% of children manifested sensitivity to noise following their mTBI. While this auditory symptom was reported as part of larger concussion questionnaires, no known study has investigated this auditory symptom specifically in children. These peripheral auditory symptoms (noise sensitivity, hearing loss, tinnitus) and impairments (damage to the peripheral structures of the auditory system) are frequently documented and observed in adults suffering from mTBI (Bergemalm & Borg, 2005; Knoll et al., 2020; White et al., 2022), the lack of data in children does not necessarily indicate the absence of these symptoms or impairment, but a need for a more thorough investigation.

1.3.2. mTBI and the central auditory system

1.3.2.1. Behavioural measures

Studies have investigated impairments/difficulties associated with the central auditory system (hereafter named central auditory processing difficulties) in children with brain injuries (Cockrell & Gregory, 1992; De Godoy et al., 2022; Deutsch & Zawel, 1966; Flood et al., 2005; Thompson et al., 2018). Among these studies, only one was conducted with children who suffered from an mTBI and gave details regarding one auditory task: listening in noise (Thompson et al., 2018). Thompson et al. (2018) measured the sentence identification ability in noise of 40 participants (20 with mTBI and 20 with orthopedic injuries) aged 8 to 16. Children with mTBI performed significantly worse on this task than children without a history of mTBI. The authors reported results regarding listening in noise, limiting the scope of these results as no other central auditory abilities were investigated. Flood et al. (2005) retrospectively analyzed the records of 31 children aged 6 to 18 with acquired brain injury. They found that of the 17 children who had abnormal results on at least one test assessing central auditory processing abilities, 9 of them (53%) had suffered a TBI. Cockrell and Gregory (1992) reviewed the records of 62 children aged 2 to 18 with moderate to severe TBI and diagnosed central auditory processing difficulties in 16% of these children. Unfortunately, important information such as the names of the utilized tests and the results' details were not fully reported in both mentioned studies (Cockrell & Gregory, 1992; Flood et al., 2005). This information would have been helpful in identifying the impaired auditory abilities in these children. Deutsch and Zawel (1966) compared the identification of sounds or words in noise of 39 children aged 6 to 12 with acquired brain damage to 39 typically developing

children. Children with acquired brain injuries performed significantly worse on the auditory tasks than controls. Since the results were not categorized according to the different types of acquired lesions (e.g., stroke, mTBI), the limited information prevented the understanding of a clear connection between central auditory processing difficulties and TBI. De Godoy and collaborators (2022) investigated central auditory processing in ten children with moderate to severe TBI by administrating seven auditory processing tests to evaluate sound localization, temporal ordering, auditory closure, temporal resolution and figure-ground in verbal monotic and dichotic listening. Temporal processing, auditory closure and binaural integration with words were altered in the majority of the children with moderate to severe TBIs in their study (De Godoy et al., 2022). These results, as well as those of Thompson et al. (2018), inform the possibility for multiple auditory processing abilities to be affected following a TBI. They are similar to results found in adult-focused studies as they confirmed signal-in-noise processing and auditory mechanisms beyond, such as dichotic listening (Vander Werff & Rieger, 2019a), can be affected following an mTBI. Overall, the results indicated that multiple auditory abilities may be affected following a mTBI. (Vander Werff & Reiger, 2019a; Hoover et al., 2017; Turgeon et al., 2011).

1.3.2.2. Neurophysiological measures

1.3.2.2.1. Auditory Late Responses (ALRs)

No studies evaluating children's ALRs following mTBI have been reported. The few studies measuring ALRs in adults with mTBI showed conflicting results (Gosselin et al., 2006; Potter et al., 2001; Rugg et al., 1988, 1993; Solbakk et al., 1999; Vander Werff & Rieger, 2019b). Significant alterations of wave components following mTBI are reported with N1 and P2 amplitude reduction responses (Gosselin et al., 2006) or N2 amplitude reduction (Solbakk et al., 1999) and N2 latency lengthening (Rugg et al., 1988, 1993). Other studies reported no significant difference in the N1 and N2 amplitude or latency (Rugg et al., 1988, 1993) between participants with mTBI and controls. All these studies were conducted under quiet conditions, indicating that mTBI does not appear to affect the ALRs systematically. A study by Vander Werff and Reiger (2019b) investigated ALRs in quiet and in noise in mTBI participants with speech sounds and a 20-talker babble noise. P2 amplitude was more reduced by the noise in the mTBI group than in the control group (Vander Werff & Rieger, 2019b). These differences between mTBI participants and controls found only in the recordings conducted in noise align with behavioural studies. Such

results are consistent with behavioural tests where mTBI participants will differ from controls only in the presence of noise (Hoover et al., 2017; Turgeon et al., 2011; Vander Werff & Rieger, 2019b). These results indicate that auditory symptoms following an mTBI may appear in more challenging (in noise) than optimal (in quiet) listening situations. Conducting ALR measures in noise could help understand how mTBI affects auditory processing in those listening environments.

Limited ALR studies have been conducted in school-aged children without an mTBI having difficulties listening in noise. These studies employed protocols that included the measurement of ALRs following auditory stimuli presented in noise (Anderson et al., 2010; Cunningham et al., 2001; Hayes et al., 2003). Cunningham et al. (2001) and Hayes et al. (2003) investigated the listening-in-noise abilities of children with learning difficulties compared to typically developing children. In both studies, amplitude and latency values of the ALRs measured in quiet were similar between groups. However, in noise, P1 or P2 and N2 amplitudes were more significantly reduced in children with learning difficulties than in controls. The authors related these results to reduced neural synchronization (Cunningham et al., 2001) and timing deficits (Hayes et al., 2003) in children with learning difficulties. These results somewhat contrast with those of Anderson et al. (2010), who reported greater amplitude of the N2 wave component in noise for children with poorer performance on a word-in-noise test than children with better performance. The authors indicated that as a smaller amplitude of the N2 wave component is generally associated with better inhibitory control or neural efficiency, a greater amplitude of the N2 wave component could be associated with difficulties perceiving auditory information in noise. These contrasting results between studies could partially arise from the differences in populations, as children diagnosed with learning difficulties' ALRs were more affected by noise than typically developing children's ALRs (Cunningham et al., 2001; Hayes et al., 2003).

These results, measuring cortical activity associated with the presentation of auditory stimuli in noise, are promising for identifying subtle central auditory processing difficulties in children with mTBI. No specific noise parameter guideline could be extracted from the current reported studies (Anderson et al., 2010; Cunningham et al., 2001; Hayes et al., 2003). All three studies utilized the verbal /da/ at 80 dB SPL (Anderson et al., 2010; Cunningham et al., 2001; Hayes et al., 2003). In addition, Hayes et al. (2003) employed a second verbal stimulus /ga/ and stimulation level, 75 dB SPL. Two types of noises were utilized: a 6-talker babble (Anderson et al., 2010) and a Gaussian

white (Cunningham et al., 2001; Hayes et al., 2003). Each study used a different signal-to-noise ratio (SNR), where the signal was equal to the noise (0 dB SNR) (Hayes et al., 2003), the signal was 5 dB louder than the noise (+5 dB SNR) (Cunningham et al., 2001) and the signal was 10 dB louder than the noise (+10 dB SNR) (Anderson et al., 2010). Further exploration of electrophysiological measurements in noise would be highly required in children. Some parameter modulations have been studied mainly in adults without central auditory processing difficulties.

Multiple parameter modulations in adults have shown that three parameters significantly impact wave component quality in noise: type of stimuli, type of noise and SNR (see pages 56-59 in Chapter 2 for a detailed literature review regarding parameter modulation). In summary, experimental parameter modulations are reported to affect ALRs in children and adults (Androulidakis & Jones, 2006; Billings et al., 2009, 2011; Gustafson et al., 2019; Maamor & Billings, 2017; Papesh et al., 2015; Small et al., 2018; Whiting et al., 1998). The SNR has been reported to have the most systematic effect when recording ALRs. In fact, the smaller the SNR, the more detrimental the effect on the ALRs (Anderson et al., 2010; Benítez-Barrera et al., 2021; Billings et al., 2009, 2013; Maamor & Billings, 2017; Papesh et al., 2015; Small et al., 2018; Whiting et al., 1998). Noise and stimulus types also have significant but not as systematic impacts on ALRs. White noise does not have an effect that is as unfavourable as babble-type noise, which produces longer latency and smaller amplitude on the ALR waveforms (Billings et al., 2011; Duquette-Laplante et al., 2024). Moreover, tonal stimuli produced shorter latencies and smaller amplitudes in children and adults than verbal stimuli (Ceponiene et al., 2005; Koravand et al., 2012, 2013). Scarcity and variability in the literature, especially in children, underline the need for further investigation of parameter modulation to find the neurophysiological marker/s most sensitive to the impacts of mTBI on central auditory processing.

1.3.2.2.2. Oscillatory activity

No known studies applying the time-frequency analysis of the impact of mTBI on stimuli in noise processing could be found in children or adults. However, a few studies were carried out with mTBI adult patients using task- or stimuli-induced oscillations. Generally, mTBI participants had significantly altered power values compared to controls (Arakaki et al., 2018; Barlow et al., 2018; Randolph & Miller, 1988; Thornton, 2003). With a visual task-switching paradigm, Barlow and collaborators (2018) found that the mTBI group had reduced accuracy on the task, coupled with

more theta desynchronization but less alpha and beta desynchronization compared to the control group. Similarly, with a working memory task (N-back: a task requiring a participant to look at a letter on a screen and press a key on a keyboard. The participant must remember the letters as if the letter that appears on the screen is the same as n-letters ago; they must press a different key), Arakaki and collaborators (2018) measured how oscillatory activity evolved following acute mTBI in participants when compared to controls. They reported an increased induced frontal alpha and more negative evoked parietal alpha were observed in participants with mTBI, indicating impaired working memory (Arakaki et al., 2018). Thornton (2003) conducted a study with a memory task (the recall of four different stories), and results demonstrated different power changes between mTBI participants and controls, as mTBI participants showed an increase in beta power for the group with brain injury and in alpha power for the control group (Thornton, 2003). Those findings echo Randolph and Miller's (1988) results as they utilized cognitive tasks with mTBI participants and found that increased variability in performance on the tasks also increases variability in the beta band. All studies reported changes in neural communication and impaired functions in the mTBI group (Arakaki et al., 2018; Barlow et al., 2018; Randolph & Miller, 1988; Thornton, 2003).

However, no studies were found in adults with mTBI using auditory stimulation in noise. Auditory processing in noise was evaluated in normal adults using an ITPC analysis (Koerner & Zhang, 2015). Koerner and Zhang (2015) measured P1 and N2 responses and ITPC values of verbal stimuli in quiet and noise. They reported smaller P1 and N2 amplitudes, longer latencies, and decreased ITPC values in noise. Moreover, they correlated ITPC values with N1 and P2 latencies and amplitudes, reporting that decreasing ITPC values were related to increasing latencies and reducing amplitudes with noise modulations. In children, Momtaz and collaborators (2021) compared children with auditory processing disorders (APD) to typically developing controls with a tonal stimulus in a quiet condition. They reported that children with APD had stronger beta-gamma phase-locking values than controls and linked these results to an imbalance of the auditory neural activity. Similarly, Gilley et al. (2016) computed the power in all the five frequency bands (delta, theta, alpha, beta and gamma) in three groups of children: with APD, with listening difficulties, and typically developing, by using a verbal stimulus in quiet and in white noise with +3 dB SNR. The power values in the gamma and theta frequency bands were reduced in noise in all groups. The results demonstrated that children with listening difficulties and with APD showed an early decoupling in the beta and gamma bands – generally associated with sensory gating and

auditory processing – which was not seen in typically developing children. Gilley et al. (2016) suggested that these differences could be connected to auditory processing deficits. In summary, such analysis methods, while still rare, are promising in identifying impaired or altered neural communication. Time-frequency analysis could be a powerful tool in quantifying subtle differences in auditory processing between mTBI and typically developing children.

In conclusion, exploring the literature on the impact of mTBI on the auditory system highlighted significant gaps, particularly in pediatric populations. Even if peripheral auditory symptoms/disabilities in children with mTBI, such as tinnitus or noise sensitivity, seem rare, further exploration is needed as they are highly prevalent in adults with mTBI (Knoll et al., 2020), and noise sensitivity is often reported by children when reviewing post-mTBI questionnaires (Lyons et al., 2022). Central auditory processing symptoms/disabilities were also underexplored, with only a few studies comprehensively addressing abilities like listening in noise or assessing central auditory abilities. Neurophysiological measures like AEPs and Time-Frequency analysis have received minimal attention in children with mTBI.

Knowledge regarding how the auditory system is affected following mTBI is paramount. Auditory difficulties can impact a child's life in multiple ways and can make every aspect of the child's life harder. Children who suffer from auditory difficulties have more difficulties at school (Crandell & Smaldino, 2000; Johnson et al., 2009; Murgia et al., 2023; Rosenberg et al., 1999), are less motivated (Evans & Lepore, 1993; Hornickel & Kraus, 2011), and are more fatigued (Eckert et al., 2016; Key et al., 2017). Communication is also important for children's interpersonal relationships and development. More investigations are required to explore how mTBI affects central auditory processing, particularly in challenging listening environments, to guide identification and intervention strategies.

1.4. Objectives

The current thesis examined school-aged children's auditory processing abilities/functions and listening behaviours following mTBI. More specifically, the aims of the thesis are (1) to document auditory processing and cognitive abilities in children with mTBI, (2) to investigate children's and their parents' perceptions regarding listening behaviours and mTBI symptoms, (3) to identify a

neurophysiological marker of auditory dysfunction following mTBI, and (4) to explore changes over time, comparing participants in acute versus chronic stages following the injury.

1.4.1. Methodology overview

To achieve all four aims, a prospective cohort study with comparison was conducted in 8–12-year-old children. They were targeted for three reasons: (1) There is no normative data for behavioural auditory processing tests for children 5 years old and younger; (2) in 6- and 7-years old children, performance in certain behavioural auditory processing tests is highly variable and therefore difficult to interpret; (3) in teenagers (13 years old and older) performance on behavioural auditory processing tests are adult-like. Two experiments were prepared (see Figure 4). The first was a behavioural experiment related to aims 1, 2 and 4. Central auditory processing tests, a cognitive screening battery and questionnaires were used. The second was an electrophysiological experiment associated to aims 3 and 4. Cortical evoked responses with auditory stimuli in quiet and in noise were recorded. To select the recording parameters for this electrophysiological study, a pre-experiment was conducted. The pre-experiment included multiple recording parameters in noise resulting in 2 quiet conditions and 12 noise conditions, investigated in young adults and school-aged children with typical development.

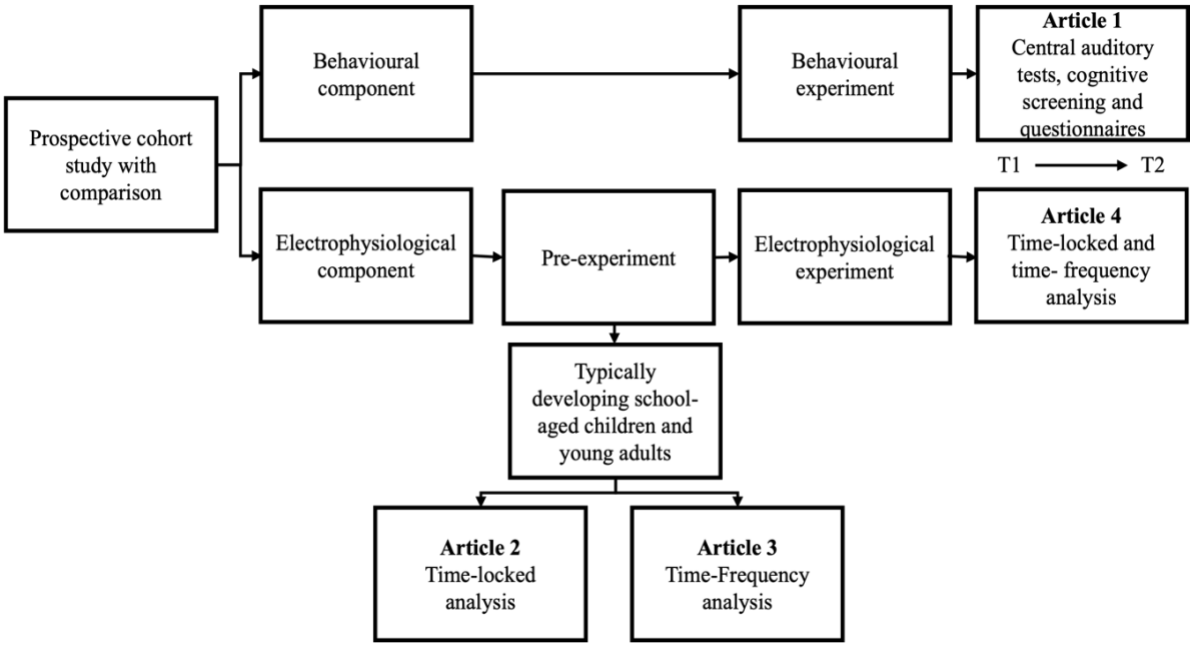

Figure 4. Thesis project organization.

1.4.2. Hypothesis

When compared to controls, some children with an mTBI will have altered auditory function. As difficulties are known to maintain, appear or resolve following a mTBI, these variations should be reflected in children's behavioural test scores, questionnaire results or neurophysiological responses (Zemek et al., 2016). In a subset of children, their behavioural test scores (De Godoy et al., 2022; Thompson et al., 2018), their perception of listening behaviours, and their parents' perception of listening behaviours (Knoll et al., 2020; Lyons et al., 2022) will be significantly poorer when compared to controls. For the neurophysiological measures, a neural marker of auditory impairment in noise induced by mTBI will be identified by elongated latencies and reduced amplitudes or phase values for a subset of the mTBI participant group (Cunningham et al., 2001; Hayes et al., 2003; Vander Werff & Rieger, 2019b).

1.5. Ethics

The current thesis required human data collection. The thesis complies with ethics committees at the Centre Hospitalier Universitaire Sainte Justine associated with the Université de Montréal (MP-21-2020-2618), the University of Ottawa (H-07-20-5557) and McGill University (CUSM) (MEO-21-2023-9276). Letters of support and consent forms for the current research project can be found in Appendix A.

CHAPTER 2. Behavioural experiment

2.1. Aim

This chapter, composed of one article, aims to answer three of the four aims of the current thesis. To provide information relating to auditory processing and cognitive abilities in children with mTBI and to document perceptions regarding listening behaviours and mTBI symptoms for children and their parents. To document how those central auditory processing and cognitive screening tests results as well as listening behaviours questionnaire scores change over time.

2.2. Methodology

The following article represents the behavioural study (see Figure 4, Chapter 1. Introduction, p. 17). Six behavioural central auditory processing tests, a computerized cognitive screening and three questionnaires were utilized with 11 children with mTBI and 10 age and sex matched control children at two measuring times: T1 – within 14 days of the injury (within days to weeks following recruitment for controls) and T2 – three months later (see p. 25 to 29 for detailed methodology).

2.3. Article 1

The article, in the following form, was published in the *International Journal of Audiology*.

Duquette-Laplante, F., Jutras, B., Gravel, J., Beauchamp, M. H., Ratelle, J., Gagnon, I., & Koravand, A. (2024). Central auditory processing and cognitive abilities after mild traumatic brain injury in school-aged children. *International Journal of Audiology*, 1–10. https://doi.org/10.1080/14992027.2024.2424871

Title

Central auditory processing and cognitive abilities after mild traumatic brain injury in school-aged children

Author names and affiliations

Fauve Duquette-Laplante [a,b,c], Benoît Jutras [b,c], Jocelyn Gravel[c,d], Miriam H. Beauchamp,[c,e], Justine Ratelle[f], Isabelle Gagnon[g,h] & Amineh Koravand[a]

a. Audiology and Speech Pathology Program, School of Rehabilitation Sciences, University of Ottawa, 200 Lees Avenue, room 261, Ottawa ON, K1N 6N5.
b. School of Speech-Language Pathology and Audiology, Université de Montréal, PO Box 6128, succ. Centre-ville, Montréal, Canada, H3C 3J7.
c. Azrieli Research Center, CHU Sainte-Justine, 3175, Côte Sainte-Catherine, Montréal, Québec, Canada, H3T 1C5.
d. Pediatric emergency department, CHU Sainte-Justine, 3175, Côte Sainte-Catherine, Montréal, Québec, Canada, H3T 1C5.
e. Psychology Department, Université de Montréal, PO Box 6128, succ. Centre-ville, Montréal, Canada, H3C 3J7.
f. Audiology department, CHU Sainte-Justine, 3175, Côte Sainte-Catherine, Montréal, Québec, Canada, H3T 1C5.

g. School of Physical and Occupational Therapy, McGill University, 3630 Promenade Sir-William-Osler Montréal, Québec, Canada H3G 1Y5
h. Child Health and Human Development Program, Research Institute of the McGill University Health Center, and Montreal Children's Hospital, McGill University Health Center, 1001 Decarie Blvd, Montréal, Québec, Canada, H4A 3J1.

email addresses:

Corresponding author

Fauve Duquette-Laplante,

Declaration of interest

The authors have declared that no conflict of interest existed at the time of publication.

Type of paper

Research Article

Abstract

Objective: The current study aimed to explore (1) school-aged children's auditory and cognitive abilities and (2) their perceptions (self-reported and parents) of listening behaviours and symptoms following mild traumatic brain injury (mTBI).

Design: Prospective cohort study.

Study Sample: Twenty-one children aged 8 to 12 participated in this study. Eleven children with mTBI were diagnosed in the emergency department, and 10 were matched controls. They were assessed twice, in the acute (≤14 days) and chronic (≥3 months) stages post-injury, using six central auditory behavioural tests, a cognitive screening battery and questionnaires. ANOVA and correlation analysis were performed.

Results: Group differences were present in three auditory tests as children with mTBI obtained poorer scores than controls (Pitch Pattern Sequence Tests - PPST: p =.037; Gap In Noise test - GIN threshold: p =.046; Duration Pattern Test - DPT: p =.053), but not for perceived listening behaviours and cognitive abilities. Correlations were found only between perceived listening behaviours and reported mTBI symptoms for parents (p =.014) and children (p =.002).

Conclusions: Auditory abilities, mostly those related to temporal processing, were affected following mTBI, independently of cognitive abilities. Better identification of auditory processing difficulties following mTBI will improve treatment and resource allocation for children.

Keywords

mTBI, mild traumatic brain injury, central auditory processing, pediatric, audiology

1. Introduction

Mild traumatic brain injury (mTBI) affects at least three million children worldwide annually (Dewan et al., 2016). For 70-90% of these children, total resolution of symptoms occurs within the first four weeks following the injury (Zemek et al., 2016), but in a minority of children, sequelae can last months to years (Fried et al., 2022). Commonly

reported symptoms include headaches, nausea, fatigue, difficulty concentrating and remembering, vision and balance problems, dizziness, irritability, sadness, nervousness and sensitivity to light and noise (Lyons et al., 2022). With its complex pathophysiology and heterogenous injury mechanism, mTBI can affect multiple domains, such as emotional, physical, cognitive or sensory functioning (Babikian et al., 2015; Lyons et al., 2022).

The central auditory system structures have been shown to be vulnerable to damage sustained following mTBI, therefore hindering its ability to process auditory information (Broglio et al., 2016; Vander Werff, 2012). As children spend extensive hours in noise or challenging listening environments, evaluating their auditory function is primordial. There is some evidence that auditory symptoms (Lyons et al., 2022; Zemek et al., 2016) and possible auditory dysfunction (Thompson et al., 2018) have been reported following mTBI in children. Lyons et al. (2022) found that 13% of their 5-17 years old participants reported sensitivity to noise, which is one of the predictors of lasting post mTBI symptoms (Zemek et al., 2016). Poorer listening skills in noise were also documented in children following mTBI (Thompson et al., 2018). Thompson et al. (2018) found that children aged 8 to 16 years with TBI performed worse when identifying sentences in noise than their peers without a history of TBI. Unfortunately, the literature is limited, and the extent of auditory symptoms and sequelae after pediatric mTBI is unknown.

In adults, auditory difficulties have been reported and measured consistently following mTBI (Turgeon et al., 2011; Vander Werff & Rieger, 2019a). Multiple auditory difficulty profiles were found reflecting the heterogenous nature of the injury; the functional aspects of auditory processing such as discrimination, temporal processes, listening in noise or degraded conditions have been altered following mTBI (Turgeon et al., 2011; Vander Werff & Rieger, 2019a). As mTBI can affect multiple aspects of functioning, Vander Werff and Reiger (2019a) investigated auditory difficulties following mTBI and their relationship to cognitive difficulties. In real world settings, auditory and cognitive difficulties can appear similar. They reported that while cognitive difficulties can affect auditory processing tests results, 32% of the mTBI participants failed auditory tests such as dichotic listening or speech-in-noise even when they exerted enough effort during testing. This

indicated that auditory processing difficulties can be present even without cognitive difficulties and that both should be evaluated following mTBI.

Studies in children without mTBI have shown associations between cognitive and auditory processing abilities (Tomlin et al., 2015; Seeto et al., 2021). These results emphasize that both cognitive and auditory skills should be considered when evaluating auditory function. Cognitive symptoms, such as difficulty concentrating and remembering or answering questions slowly, are often reported by children and their parents following mTBI (Lyons et al., 2022; Zemek et al., 2016). However, studies showed that persistent cognitive difficulties following mTBI only arise in some cases (Beauchamp et al., 2018; Lambregts et al., 2018). Beauchamp et al. (2018) found that a small proportion of children (4.5% of the 311 children 6-17 years of age) had cognitive difficulties 12 weeks after mTBI. Multiple aspects of cognition can be affected following mTBI. Lambregts et al. (2018) evaluated 73 participants (6-22 years old) with mTBI with a neuropsychological test battery. They reported reduced processing speed, inhibitory control, cognitive flexibility, visuospatial constructional ability and visuospatial memory in 7-15% of their participants two years following their injury.

In summary, the relationship of auditory and cognitive function is complex and both auditory and cognitive difficulties have been reported following mTBI (mostly in adults). As the literature on auditory difficulties following pediatric mTBI is sparse, the present study (1) explored auditory abilities in children with mTBI, (2) screened their cognitive abilities, and (3) investigated the perception of listening behaviours of these children from two perspectives: the children with mTBI and their parents.

2. Methods

2.1. Ethics

The present study was approved by the CHU Sainte-Justine (MP-21-2020-2618), the University of Ottawa (H-07-20-5557), and the Pediatric committee of the McGill

University Hospital Center ethics committees (MEO-21-2023-9276). Participating families provided written consent and children provided written assent before inclusion in the study.

2.2. Study design

The current study was a prospective cohort of children with mTBI.

2.3. Setting

Recruitment occurred at the Sainte-Justine University Hospital Center and The Montreal Children's Hospital of the McGill University Health Center. These are tertiary care, University-affiliated, pediatric hospitals. Recruitment began in May 2022 and ended in November 2023. Data collection for all participants was conducted between May 2022 and March 2024.

2.4. Participants

School-aged children were recruited: children with mTBI were referred by the emergency department and the mTBI clinic of the Sainte-Justine University Hospital Center and the emergency department of Montreal Children's Hospital, McGill University Health Center; children in the control group came from the community and the Orthopedic External Clinic of the Sainte-Justine University Hospital Center.

2.4.1. Inclusion criteria

All participants were between 8 years and 12 years, 11 months, at the time of the initial recruitment. Children had French as a dominant language. Children with mTBI received their diagnosis from a physician preceding their participation in the study. They met the Quebec diagnostic criteria for mTBI, which include an alteration of cerebral function secondary to an external force applied to the head characterized by (1) a Glasgow Coma Scale score of 13-15; (2) a loss of consciousness <30 minutes; (3) an alteration of consciousness ≤ 24 hours; (4) post-traumatic amnesia ≤ one day; and (5) when conducted, brain imaging results could indicate the absence or presence of focal signs of non-surgical injury.

2.4.2. Exclusion criteria

Children who did not meet the following criteria were excluded: 1) hearing thresholds of 15 dB HL or lower at frequencies tested between 250 Hz and 8000 Hz in both ears and 2) normal middle ear function – static compliance between 0.3 and 2.5 cc and middle ear pressure between -150 and +50 daPa. Children born prematurely (<37 weeks) or with the following health conditions were excluded: chronic middle ear infections, ventilation tubes or ototoxic medications, neurological disorders such as epilepsy, developmental disorders such as autism spectrum disorder, psychiatric disorders such as obsessive-compulsive disorder, congenital conditions such as fetal alcohol syndrome, metabolic conditions such as diabetes, or attention or language disorders. Children with an intellectual disability or difficulties in school were also excluded. In both groups, children with a history of head injury before the recruitment in the current study were excluded. In the control group, children who failed one or multiple central auditory tests were excluded.

2.5. Procedure

All children were assessed twice with central auditory behavioural tests, a cognitive screening test and questionnaires: Time Measure 1 (T1) - within fourteen days following the mTBI injury, corresponding to the acute/subacute injury phase for the mTBI group (Babikian et al., 2015), and in one to three weeks after the recruitment for the control group and Time Measure 2 (T2) - three months later, usually corresponding to the beginning of the persistent phase of symptoms (Babikian et al., 2015). The order of presentation for all tests and questionnaires was randomized. Each measurement session lasted two to three hours and was separated into 2-3 testing blocks, as needed.

2.5.1. Central auditory evaluation

Six central auditory behavioural tests were chosen for the current project. Four tests were conducted monaurally: (1) The *Test de mots dans le bruit* (TMB) – Word in noise test evaluated speech-in-noise recognition (figure/ground segregation ability) with words in a babble noise (Lagacé, 2010); (2) The Gap in noise test (GIN) assessed temporal resolution with the identification of gaps in segment of noise (Shinn et al., 2009). (3) The Pitch pattern sequence test (PPST) measured frequency discrimination, sequential organization and verbal labelling (Musiek, 1994) with series of sequences of three sounds of two different frequencies. (4) The Duration pattern test (DPT) measured sequential organization,

duration discrimination and verbal labelling (Musiek, 1994) with series of sequences of three sounds of two different durations. The fifth and sixth tests were conducted binaurally: (5) The Masking level difference (MLD), where the difference between two thresholds (SΦNΦ: Threshold for signal in phase and noise in phase; SπNΦ: Threshold for signal not in phase and noise in phase) was utilized to evaluate the binaural interaction ability (Lynn et al., 1981) and (6) The *Écoute dichotique de chiffres* (EDC) – Dichotic digits test measured binaural integration with two pairs of different numbers presented simultaneously to both ears (Jutras et al., 2012) (see Supplemental Materials for test administration details). The evaluation was conducted in a soundproof booth (norms ANSI S3.1) with insert headphones (E-A-RTONE 3A) connected to the Madsen Astera 2 audiometer. This evaluation took between 90 and 180 minutes per participant. The scores in percentages for the TMB, PPST, DPT, EDC and GIN%, as well as the Gap threshold in msec for the GIN and the thresholds and the difference in dB for the MLD were employed in the group analysis. For all percentage scores and the difference in dB for the MLD, higher values indicate higher test success whereas for both MLD and GIN thresholds, smaller values indicate higher test success. To identify passing scores for the TMB, PPST, DPT, EDC and GIN, each individual score was compared to age-appropriate norms, which are calculated as a maximum of - 2 standard deviations from the mean score. For the MLD, there are no norms for the condition thresholds, but the degree of release of masking score was compared to the norm (Lynn et al., 1981).

2.5.2. Cognitive screening

The Central Nervous System Vital Signs (CNSVS) neuropsychological screening test battery was conducted on a computer in a quiet room (Gualtieri & Johnson, 2006). This screening test lasted 25 to 40 minutes and included seven subtests: Verbal Memory, Visual Memory, Finger Tapping, Symbol-Digit Coding, Stroop, Divided Attention and Continuous Performance (see Supplemental Materials for subtest description and administration). The test battery was automatically scored within the software and divided into cognitive subscales: Neurocognitive Index, Complex Attention, Cognitive Flexibility, Executive Functioning, Motor speed, Simple Attention, Processing Speed, Psychomotor Speed, Reaction Time, Visual Memory, Verbal Memory, and Composite Memory. Scores were reported in three ways: raw scores calculated from the data, standard scores calculated

via normalization (mean = 100 and SD = 15), and percentile ranks calculated from the age-appropriate normative data within the software. To identify passing or failing scores, the standard scores were separated into five categories: Above (> 110), Average (90-110), Low Average (80-89), Low (70-79), Very Low (< 70). Above and Average were classified as High to normal function, while Low Average, Low and Very Low were classified as slight deficit to moderate deficit to deficit. The standard scores for the Neurocognitive Index and the eleven cognitive skills were utilized in the subsequent group-level analysis.

2.5.3. Questionnaires

In order to assess participants' perceived auditory behaviours, children answered the French adaptation (Jutras et al., 2017) of the Listening Inventories for Education UK Individual Hearing Profile (LIFE-UK), an 18-item questionnaire assessing how children navigate listening situations in school, with questions regarding how they hear their teachers or peers in quiet or noisy situations. The LIFE-UK had a five-point Likert scale from 1 (Always Difficult) to 5 (Always Easy) for each question. The total scores for the LIFE-UK were calculated as the sum of all questionnaire answers. Parents completed the French adaptation (Gagnon et al., 2009) of the Scale of Auditory Behaviors (SAB), a 12-item questionnaire assessing the frequency of auditory processing-related difficulties such as problems with comprehension of complex instructions or speech sounds, hearing in noise, and sustaining attention. The SAB had a five-point Likert scale from Never (1) to Always (5) and the total score for the SAB was calculated as the sum of all questionnaire answers. For both the LIFE-UK and the SAB, a higher score indicated better perceived listening behaviours. In order to document post-mTBI symptoms, parents and children included in the mTBI group completed a French adaptation (Duquette-Laplante, 2020) of the Post-Concussion Symptom Inventory (PCSI) questionnaire, consisting of two versions, one for the child (PCSI-C) and one for the parent (PCSI-P). The total scores for PCSI-P and PCSI-C were calculated as the sum of all questionnaire answers where higher scores indicated higher symptom perception. Children rated their symptoms on a three-point Likert scale with 0 (not present), 1 (mild) and 2 (severe). Parents rated their child's symptoms on a 6-point Likert scale from 0 (not present) to 3 (moderate) to 6 (severe). For scoring, both versions of the questionnaires categorized symptoms into physical,

emotional, cognitive or fatigue all four categories were summed in a total symptom score. Between 5 and 10 minutes were required to complete each questionnaire.

2.6. Statistical analysis

Multiple analyses were conducted for the central auditory behavioural tests, cognitive screening test and questionnaires. Three-way mixed-factorial ANOVAs, performed with SPSS (version 29), with the central auditory behavioural test results based on the following factors and their interactions: the between-subject factor Group (two levels: children with mTBI and controls) and the within-subject factors Time (two levels: T1 and T2) and Condition (two levels: Right ear and Left ear or SπNΦ and SΦNΦ). Two-way mixed-factorial ANOVAs were utilized for the factor Group (two levels: children with mTBI and controls), the repeated measures of the factor Time (two levels: T1 and T2) and their interaction on the cognitive screening test scores as well as the scores of the questionnaires. T-tests were performed when necessary, and a Bonferroni correction factor was applied to account for multiple comparisons (p = 0.05/number of t test). Pearson's r correlations were performed with the total scores of the PCSI-P and PCSI-C, Life-UK and SAB and pooled-condition scores for each auditory test in T1 and T2.

3. Results

A total of 26 children (13 mTBI and 13 controls) provided consent to participate in the study. Five participants were excluded (see Figure 1). Finally, 21 children, including 11 with a diagnosis of mTBI (mean ± SD: 10.11 ± 1.39 years, two girls) and 10 age and sex-matched controls (mean ± SD: 10.12 ± 1.35 years, one girl) were included in the study (see Figure 1). For the mTBI participants, ten children had a Glasgow score of 15 and nine did not undergo neuroimaging. Six children were injured while practicing sports; three fell, and two were assaulted.

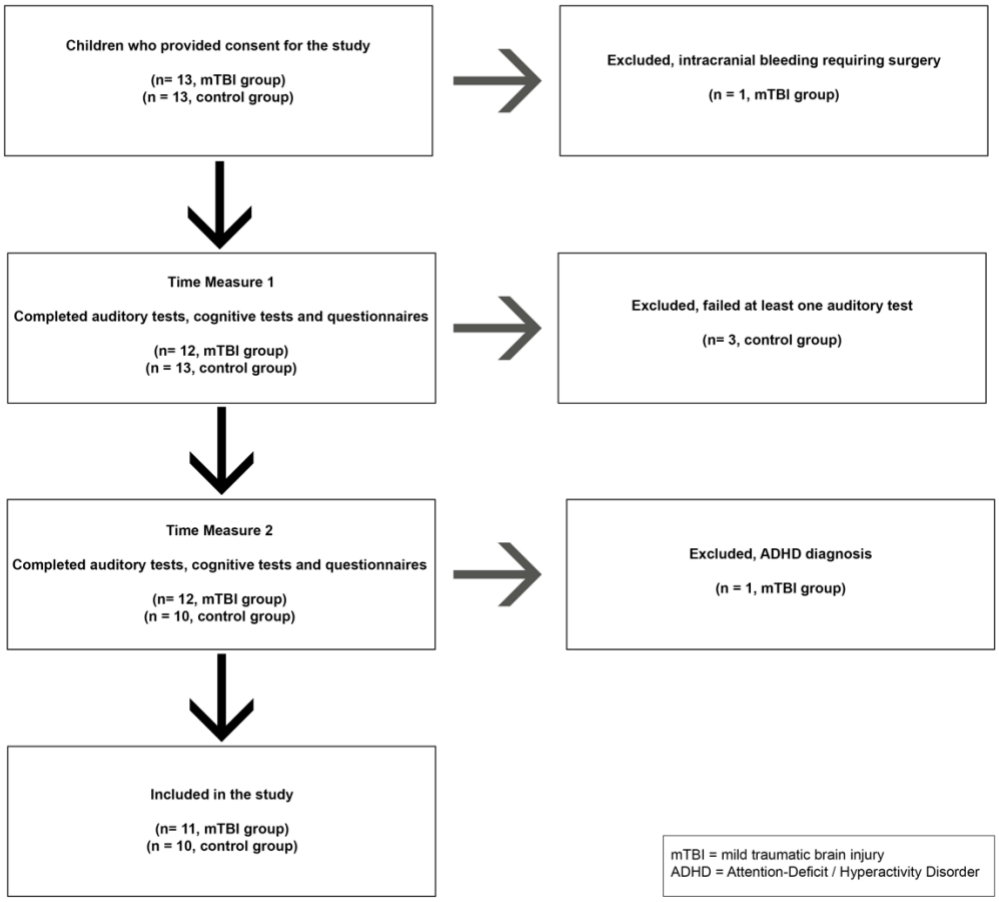

Figure 1. Participant inclusion flowchart.

3.1. Central auditory evaluation

ANOVA results are presented in Table 1. For the TMB, the two-way ANOVA yielded no significant differences between the two groups or time measures (see Figure 2A). For the GIN threshold, the main effect of the Group factor was significant [$F(1,19) = 4.556$, $p = 0.046$, $\eta^2 = 0.193$], where the control group had smaller thresholds than the mTBI group (see Figure 2B). Similar results were obtained for the GIN percentage score (see Figure 2C). The main effect of Group [$F(1,19) = 5.042$, $p = 0.037$, $\eta^2 = 0.210$] was significant, with controls having higher scores than mTBI participants. For the PPST, the main effect of Group [$F(1,19) = 4.762$, $p = 0.042$, $\eta^2 = 0.200$] and Time [$F(1,19) = 5.045$, $p = 0.037$, $\eta^2 = 0.210$] were significant. The control group scored higher than the mTBI group, and the second-time measure scores were better than the first for the two groups (see Figure

2D). When analyzing the DPT scores, the effect of the Group factor trended towards significance [$F(1,19) = 4.257$, $p = 0.053$, 2 = 0.183], where the control group had greater scores than the mTBI group. The Time effect was significant [$F(1,19) = 13.435$, $p = 0.002$, $\eta^2 = 0.414$], where the percentage of correct responses was significantly higher at the second measure time than at the first (see Figure 2E). Statistical results with the MLD scores showed that the release from masking was not significant for Group and Time (see Figure 2F). However, there was a significant effect of the MLD condition [$F(1,19) = 1070.828$, $p < 0.001$, $\eta^2 = 0.983$], where the thresholds were significantly better for the easiest condition (SπNΦ) than the more challenging condition (SΦNΦ). The effect of the Group did not reach significance [$F(1,19) = 3.982$, $p = 0.061$, $\eta^2 = 0.173$] (see Figure 2G). The only significant effect for the EDC was the main factor of Ear [$F(1,19) = 5.194$, $p = 0.034$, $\eta^2 = 0.215$], whereby results of the right ear were better than those of the left ear, independent of the group and the measure time (see Figure 2H). For all the reported ANOVAs and tests, there were no significant interactions between different factors.

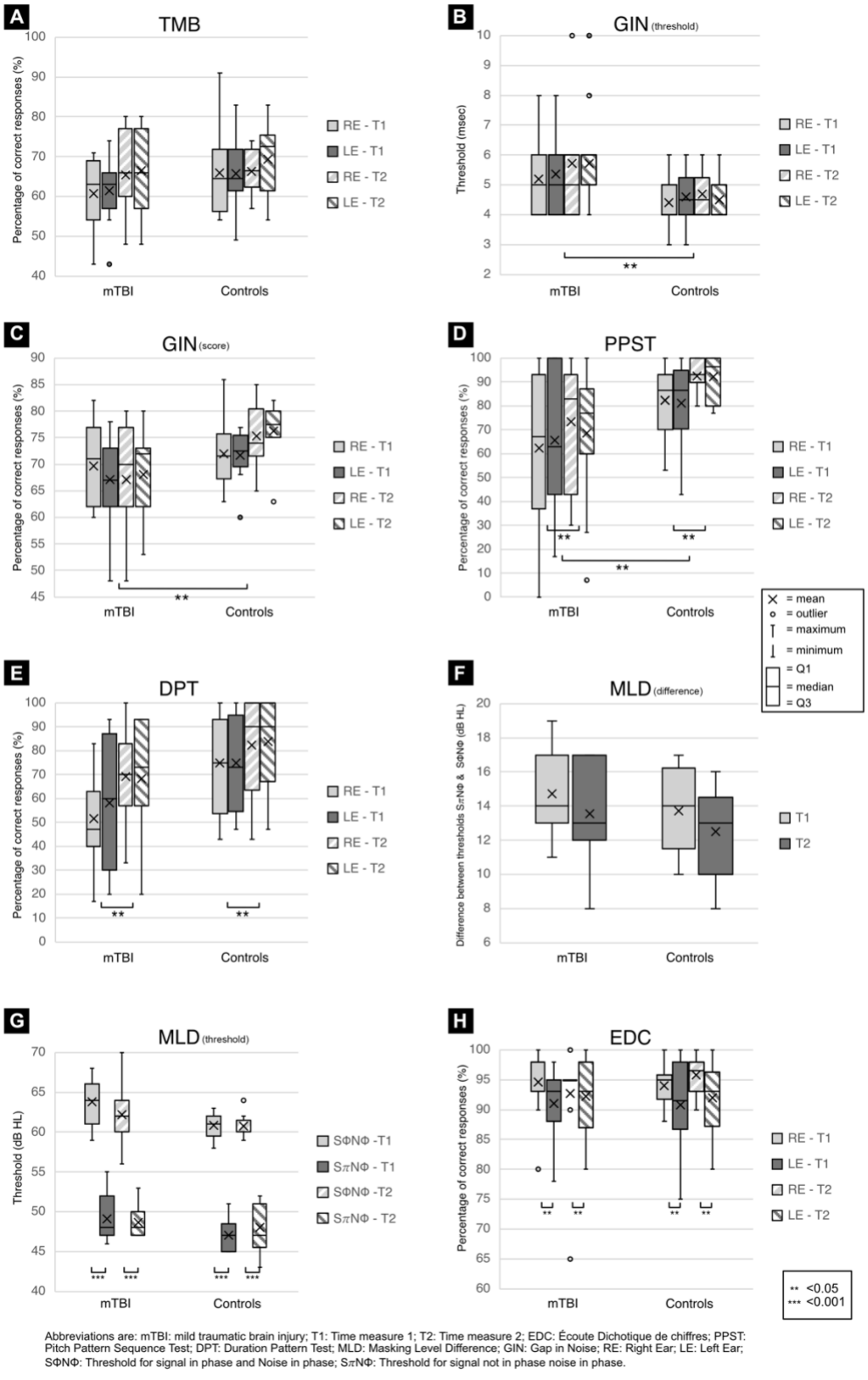

Figure 2. Central auditory behavioural test results for the mTBI groups and the control group in A) TMB, B) GIN threshold, C) GIN score, D) PPST, E) DPT, F) MLD – threshold, G) MLD – difference, H) EDC.

3.2. Cognitive screening

ANOVA results revealed no significant group effects or interactions in cognitive subscales. However, there was an effect of time in the following subscales: NCI [$F(1,19) = 8.174$, $p = 0.010$, $\eta^2 = 0.301$], Complex Attention [$F(1,19) = 5.342$, $p = 0.032$, $\eta^2 = 0.219$], Cognitive Flexibility [$F(1,19) = 28.480$, $p < 0.001$, $\eta^2 = 0.600$], Executive Functioning [$F(1,19) = 30.966$, $p < 0.001$, $\eta^2 = 0.620$]. The scores for the two groups were significantly better in Time 2 compared to Time 1. The remaining subscales – Motor speed, Simple Attention, Processing Speed, Psychomotor Speed, Reaction Time, Visual Memory, Verbal Memory, and Composite Memory – had no significant result (see Table 1).

Table 1. Mean and standard deviation of central behavioural auditory test scores, standard cognitive screening test scores and total questionnaire scores in percentage for the control and the mild traumatic brain injury (mTBI) groups at the two-time measures. Only the significant effects are reported.

			Control		mTBI		Significant	*p*
Test	Time	Condition	mean	SD	mean	SD	Effect	
Behavioural auditory tests								
Ecoute Dichotique de chiffre (EDC)	Time 1	Right Ear	94.0	3.8	94.6	5.9	Ear	0.034
		Left Ear	90.8	7.6	91.0	6.4		
	Time 2	Right Ear	95.8	3.1	92.7	9.6		
		Left Ear	92.0	6.2	92.2	6.1		
Pitch Pattern Sequence Test (PPST)	Time 1	Right Ear	82.2	14.8	62.4	32.8		
		Left Ear	81.1	18.4	65.6	29.3	Time	0.037
	Time 2	Right Ear	92.5	7.3	73.3	24.2	Group	0.042
		Left Ear	92.3	9.6	68.5	29.1		
Duration Pattern Test (DPT)	Time 1	Right Ear	74.8	20.5	51.5	19.4		
		Left Ear	74.8	20.6	58.1	26.6	Time	0.002
	Time 2	Right Ear	82.3	20.7	69.1	20.8	Group	0.053
		Left Ear	83.7	17.9	68.2	23.5		
Test de mots dans le bruit (TMB)	Time 1	Right Ear	66.0	11.8	60.7	9.2		
		Left Ear	65.7	9.3	61.4	8.2		
	Time 2	Right Ear	66.3	5.7	65.5	10.8		
		Left Ear	69.3	9.6	66.4	11.1		
Gaps in Noise (GIN) threshold	Time 1	Right Ear	4.4	0.8	5.2	1.3		
		Left Ear	4.6	1.0	5.4	1.2		

Gaps in Noise (GIN) percentage score	Time 2	Right Ear	4.7	0.8	5.6	2.3	Group	0.037
		Left Ear	4.5	0.7	5.5	2.0		
	Time 1	Right Ear	71.9	6.7	69.7	7.4		
		Left Ear	71.7	5.1	67.2	8.3		
	Time 2	Right Ear	75.3	6.0	67.2	11.1		
		Left Ear	76.3	5.3	68.1	8.8		
Masking Level Difference (MLD)	Time 1	SϕNϕ	60.9	1.5	63.8	3.0	Condition	< 0.001
		SπNϕ	47.2	2.1	49.1	2.9		
	Time 2	SϕNϕ	60.9	1.4	62.2	3.7		
		SπNϕ	48.4	3.2	48.6	1.9		
	Time 1	Difference	13.7	2.7	14.7	2.6		
	Time 2	Difference	12.5	2.6	13.5	2.8		
Neuropsychology screening test								
Neurocognitive Index	Time 1		97.1	10.7	96.1	12.3	Time	0.01
	Time 2		102.1	8.1	103.5	11.4		
Composite Memory	Time 1		100.0	15.5	95.0	18.3		
	Time 2		98.3	20.0	100.5	16.8		
Verbal Memory	Time 1		92.9	20.9	91.5	21.7		
	Time 2		92.9	21.6	102.2	17.6		
Visual Memory	Time 1		106.3	14.1	100.3	15.1		
	Time 2		103.7	14.8	99.4	15.3		
Psychomotor Speed	Time 1		100.0	13.2	105.0	15.8		
	Time 2		104.0	15.6	106.3	16.3		
Reaction Time	Time 1		88.7	20.8	91.9	32.3		
	Time 2		93.3	19.1	103.2	20.0		
Complex Attention	Time 1		99.1	11.9	94.8	10.9	Time	0.032
	Time 2		105.4	14.0	102.3	9.0		
Cognitive Flexibility	Time 1		96.5	13.3	93.6	13.6	Time	< 0.001
	Time 2		109.2	11.3	105.1	10.8		
Processing Speed	Time 1		100.9	11.1	100.4	14.9		
	Time 2		107.2	12.7	104.3	14.1		
Executive Functioning	Time 1		98.2	13.5	94.5	13.8	Time	< 0.001
	Time 2		110.8	11.6	107.6	10.7		
Simple Attention	Time 1		93.9	13.2	90.3	18.2		
	Time 2		93.8	22.0	88.5	23.8		
Motor Speed	Time 1		99.5	15.3	107.0	17.0		
	Time 2		101.1	17.3	105.9	16.7		
Questionnaires								
Life UK	Time 1		78.2	7.7	72.0	13.5	Time	0.017

	Time 2	82.2	4.2	76.4	9.6		
SAB	Time 1	50.3	4.5	46.0	10.2		
	Time 2	49.1	5.1	44.1	11.5		
PCSI - Children version	Pre-injury			2.1	2.9		
	Time 1			11.2	8.5	Time	0.002
	Time 2			5.7	5.9		
PCSI - Parent version	Pre-injury			9.0	9.8		
	Time 1			40.0	33.9	Time	0.011
	Time 2			16.3	14.1		

Abbreviations: SD: standard deviation; SΦNΦ: Threshold Signal in phase, Noise in phase; SπNΦ: Threshold Signal not in phase, Noise in phase.

3.3. Questionnaires

For the Life-UK questionnaire, ANOVA results showed that only the main effect of Time [$F(1,19) = 6.862$, $p = 0.017$, $\eta^2 = 0.265$] was significant, as the questionnaire's total score was higher for the second than for the first measure time, indicating better perceived listening behaviours at T2. Results for the SAB questionnaire did not reveal any significant effects of the main factors, Group and Time, or nor for the interaction between these two factors (see Table 1).

Exploratory correlation analysis for T1 and T2, between questionnaire total scores and auditory test results (pooled for conditions), revealed very few significant correlations. As the number of participants was limited, only strong (>.70) correlations were reported. For T1, the PCSI-C is negatively correlated [$r(9) = -.713$, $p = .014$] to the Life-UK, indicating that the better the scores on the Life-UK, the lower the symptoms on the PCSI-C. For T2, the PCSI-P had two correlations, a positive correlation [$r(9) = .822$, $p = .002$] to the pooled conditions of the MLD results, indicating that the better the thresholds, the lower the symptoms for the questionnaire and a negative correlation [$r(9) = -.817$, $p = .002$] to the SAB indicating the worse scores reported on the SAB, the more symptoms reported on the PCSI-P.

4. Discussion

Information regarding the impact of mTBI on auditory function in children is scarce, therefore the current study aimed to investigate auditory and cognitive function as well as

perceived auditory behavioural in children following mTBI. The findings of this study show that children with mTBI had poorer scores on a subset of the central auditory processing tests, but did not have poorer score on a cognitive screening or in perceived listening behaviours compared to children without mTBI.

4.1. Central auditory evaluation

Overall, when comparing all children's score to normative data (see Figure 3) differences between groups are similar to statistical analysis results. For both T1 and T2, 7 children in the mTBI group failed one or more tests at least -2 SD from the mean. And 6 and 5 children failed two or more tests at T1 and T2 respectively. Such results are clinically significant, indicating that children have auditory processing difficulties and require follow-up and treatment (Canadian Interorganizational Steering Group for Speech-Language Pathology and Audiology, 2012).

Previous studies indicate that participants with mTBI generally have abnormal results on both word-in-noise and speech-in-noise tests (Thompson et al., 2018; Turgeon et al., 2011; Vander Werff & Rieger, 2019a). The current study conducted one word-in-noise test, the TMB, a French version of the Word In Noise (WIN) test (Lagacé, 2010). In contrast to previous studies, the TMB scores were not significantly different between groups. This contradicts Thompson et al. (2018), who reported that children had difficulty with speech in noise following a mTBI. These authors utilized the HINT, a sentence in the noise test, versus the TMB in the current study, a word in the noise test. Differences between tests go beyond word versus sentence. The TMB is scored with a percentage of correct answers and its noise level remains stable throughout the test. The HINT's noise level is adaptative where a threshold of sentence identification in noise is how the test is scored. The increased complexity and effort related to the identification of a sentence in adaptable noise levels versus only a word at one noise level could explain, in part, the lack of sensitivity of the word in noise test and suggest the need to use more complex and adaptative speech-in-noise tests in children with mTBI. In addition to the TMB, the EDC and the MLD were also not significantly different between groups and were failed by only one or less participants at either T1 or T2. A review of these tests and their inclusion in a mTBI test battery should be performed.

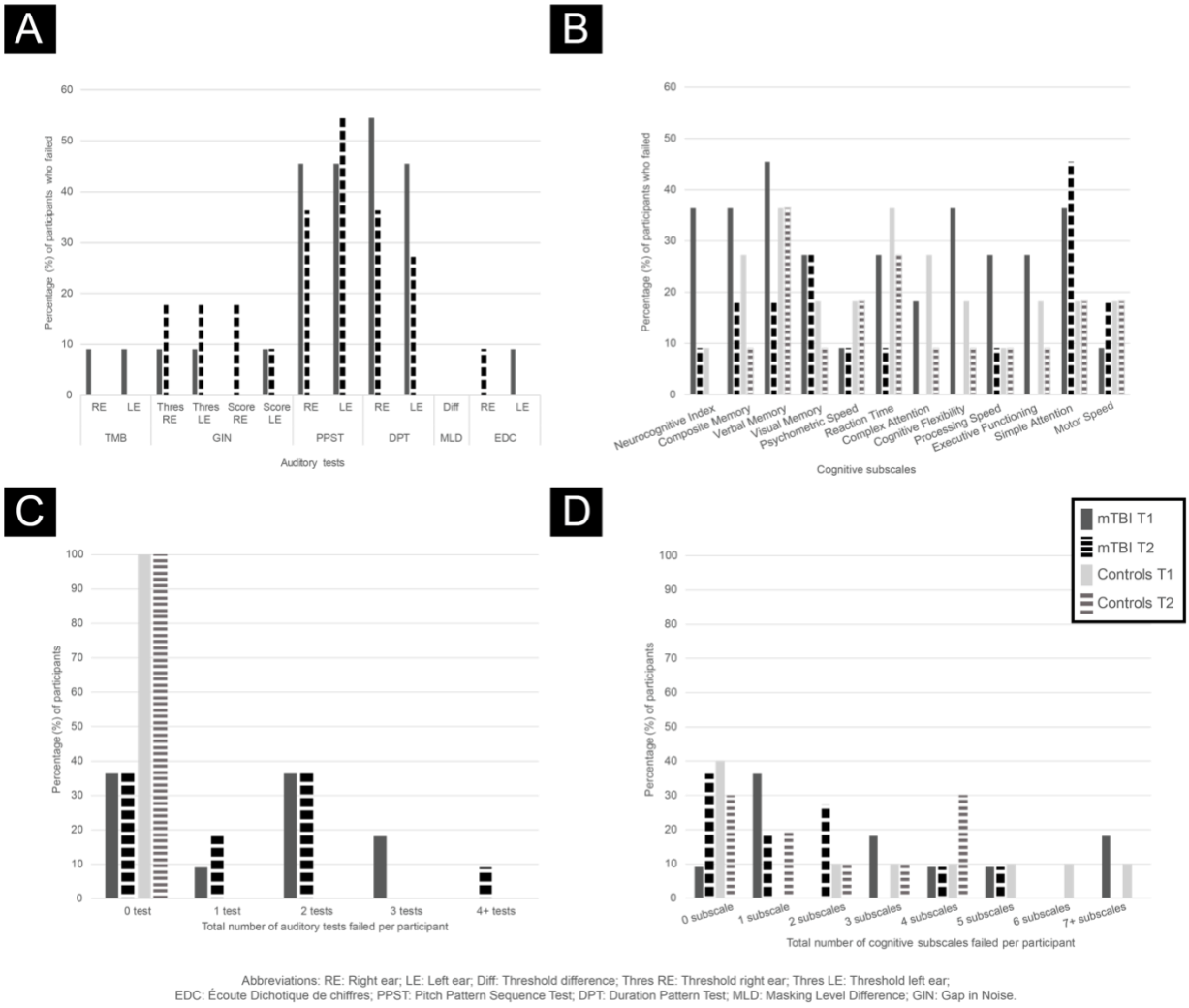

Figure 3. Percentage of participants with abnormal results at the two measure times for each test: A. Central auditory evaluation and subscale, B. Cognitive screening; and percentage of participants with abnormal results for total number of tests failed: C. Central auditory evaluation or subscales D. Cognitive screening.

In the current study, the most failed tests for participants with mTBI were those of temporal processing (PPST, DPT and GIN), which were aligned with the significant or near-significant group differences. Deficits in temporal processing (labelling and resolution) reported in children with mTBI echoed results obtained in athletes with mTBI (Białuńska & Salvatore, 2017; Turgeon et al., 2011) and children with moderate to severe TBI (De Godoy et al., 2022). Turgeon et al. (2011) reported abnormal temporal processing in a subset of their participants with mTBI and De Godoy et al. (2022) found significant difficulties in temporal ordering and in temporal resolution in respectively 80% and 40%

of their participants. Bialunska and collaborators (2017) reported temporal processing deficits as they investigated altered auditory comprehension following mTBI in adolescents and adults. They showed that even when mTBI participants improved, they were less sensitive to temporal cues than non-mTBI participants. Similarly, in the current study, both groups improved from T1 to T2 for PPST and DPT, yet overall performance differences indicated that these tests were significantly harder for participants following mTBI. Moreover, for all children who failed the labelling component of the temporal processing test (PPST), frequency discrimination and ordering were intact. Such results have also been reported in participants who underwent a complete resection of the corpus callosum; they had difficulty labelling but not humming their responses (Musiek et al., 1980). Post-mTBI pediatric imaging results are heterogenous, but certain studies show functional and structural group differences in the white matter/corpus callosum region (see Schmidt et al., 2018 for a systematic review). Taken together, these results show that temporal processing tests should be assessed following mTBI.

4.2. Cognitive screening

In contrast, cognitive screening test results did not reveal any significant differences between the mTBI and the control group. CNSVS cognitive screening results showed greater variability than the central auditory tests, as children in both control and mTBI groups failed CNSVS subtests at T1 and T2. As seen in Figure 3, some participants in the control group failed subtests of the CNSVS but not central auditory tests, whereas some participants with mTBI failed both types of tests. This is also shown in adults, as Vander Werff and Rieger (2019a) documented auditory and cognitive difficulties in adults with an mTBI. They reported that while auditory and cognitive symptoms can appear similar, when tested, their participants had abnormal performances at higher rates on auditory tests than on cognitive tests. These results indicated that a subset of mTBI patients experience auditory deficits and not necessarily a secondary effect of cognitive difficulties (Vander Werff & Rieger, 2019a). In the current study, the cognitive screening test could not distinguish between mTBI and controls. Multiple children in the control group had standard scores below 90, classified from Low Average to Very Low (<70) in multiple subscales of the cognitive screening (see Figure 3), which could explain, in part, the absence of significant differences between groups for this test category. Moreover, for the current

study, the CNSVS, a cognitive screening and not a cognitive test battery was utilized, which could indicate that it was not sensitive enough to detect cognitive difficulties following mTBI. Subsequent studies could explore the possibility of including a full neuropsychological assessment instead of a screening, as well as excluding children in the control group with previously established criteria for neurocognitive impairment: two or more test scores at -1.5 SD from the mean (Beauchamp et al., 2015).

4.3. Questionnaires

Similar to the cognitive screening results, the listening behaviour questionnaires, the Life-UK and the SAB did not show significant group differences. Both questionnaires have been found to correctly identify children at risk of auditory difficulties (Nunes et al., 2013; Purdy et al., 2018). However, their efficiency has been modulated by different parameters, such as the length of the questionnaire for the Life-UK (Purdy et al., 2018) or the presence of comorbidities in the studied populations for the SAB (Effat et al., 2011). Purdy et al. (2018) reported auditory perception differences between controls and children with auditory processing disorder (APD) or listening difficulties with a simplified version of the LIFE-UK. These results may suggest that the Life-UK, in its original version, might not be the most sensitive or appropriate questionnaire for documenting listening difficulties following an mTBI. Effat et al. (2011) investigated differences in reported listening behaviours with the SAB questionnaire in children with attention deficits (ADHD) and children with auditory deficits (APD). Overall scores on the questionnaire were low, failing to distinguish disorders, indicating the possibility that children with cognitive difficulties also present with reduced SAB scores. In the current study, while questionnaire scores for both the Life-UK and the SAB were not significantly different between groups, average scores were lower for the mTBI group than the control group. Moreover, in mTBI children, correlations between the SAB and the PCSI-P and between the Life-UK and the PCSI-C indicated that perceived poorer auditory listening behaviours were associated with the greater presence of perceived mTBI symptoms by both parents and children. Further investigation of both the SAB and the LIFE-UK questionnaires and their items in more mTBI participants and controls could help understand how specific reduction in listening behaviours is related to post-mTBI symptoms and how and if they indicate further auditory deficits. The continued use of auditory-specific questionnaires is warranted.

5. Clinical Implications

It has been previously established that evaluations beyond the peripheral auditory assessment are warranted following mTBI (Białuńska & Salvatore, 2017; De Godoy et al., 2022; Turgeon et al., 2011; Thompson et al., 2018; Vander Werff & Rieger, 2019a). In fact, as children spend most of their lives in challenging listening situations and with cognitive and auditory difficulties appearing similarly in such settings, assessing and identifying difficulties processing auditory information is paramount in providing appropriate rehabilitation and treatment. In adults with mTBI, Buriti & Gil (2022) found that formal auditory training could improve performance on multiple tests of central auditory processing, such as sound localization, speech in noise, verbal memory, and temporal ordering and labelling. Their study found that those improvements were present and maintained six months after the auditory training.

In children following mTBI, such rehabilitation is a great avenue to explore. Unfortunately, no studies could be identified. However, in children with auditory difficulties, research has shown that a combination of auditory training and technological aids (FM systems) could improve children's performance on central auditory tests and at school (Sharma et al., 2012). Such protocol could be adjusted and utilized with children with auditory difficulties following mTBI.

6. Limitations

The small sample of children limited the statistical power and did not allow a thorough generalization of the results obtained in the present study. The extensive exclusion criteria also reduced generalizability of the findings to a broader school-aged mTBI population. The number of girls and boys included was not well-balanced. Recent literature is contradictory as some studies do not report sex differences in mTBI post-concussion symptom outcomes in pre-adolescent children (Yeates et al., 2022). At the same time, girls are also reported to have slower recovery (Zemek et al., 2016). Nevertheless, future studies should have strategies for including more girls in their sample, as, in this age group, it is reported that they represent 40% of mTBIs (Zemek et al., 2016). Overall, the testing environment did not mirror real-life functional demands of children with mTBI. The assessment session was long and could have caused children to lose motivation and reduce

performance when completing various tests. This combination could lead to a better understanding of specific auditory difficulties following mTBI. Finally, multiple aspects of the protocol utilized in the current study could be revised as lasting difficulties following mTBI are uncommon. Therefore, it is possible that not all participants sustained auditory deficits as a result of the mTBI.

7. Conclusions

The current study aligns with pediatric mTBI literature, suggesting that sensory and cognitive outcomes after the injury are heterogeneous (Beauchamp et al., 2018; Białuńska & Salvatore, 2017; Vander Werff & Rieger, 2019a). Moreover, results indicated that children with mTBI may be at risk of auditory processing difficulties independently of cognitive abilities. Parents and children in the mTBI group reported post-mTBI symptoms, but their perceptions regarding listening behaviours did not significantly differ from those of the control group. A more thorough evaluation of possible auditory symptoms and dysfunctions following mTBI will lead to the development of more sensitive tools to detect subtle dysfunctions following mTBI, which could inform more efficient and earlier interventions for these children.

8. Acknowledgments

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9. Data availability statement

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

10. Authors contributions

Fauve Duquette-Laplante: Conceptualization; Data curation; Formal Analysis; Funding Acquisition; Investigation; Methodology; Project administration; Software; Supervision;

Validation; Visualization; Writing - Original Draft Preparation; Writing – review and editing. **Benoît Jutras**: Conceptualization; Formal Analysis; Funding Acquisition; Methodology; Project Administration; Resources; Supervision; Validation; Writing - Original Draft Preparation; Writing – review and editing. **Jocelyn Gravel**: Conceptualization; Funding Acquisition; Methodology; Project administration; Writing – review and editing. **Miriam Beauchamp**: Conceptualization; Funding Acquisition; Methodology; Writing – review and editing. **Justine Ratelle**: Funding Acquisition; Writing – review and editing. **Isabelle Gagnon**: Project administration; Writing – review and editing. **Amineh Koravand**: Conceptualization; Formal Analysis; Funding Acquisition; Methodology; Project administration; Resources; Supervision; Writing - Original Draft Preparation; Writing – review and editing.

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Supplemental material

Test and questionnaire descriptions

1. Central auditory evaluation test descriptions

1.1. Test de mots dans le bruit (TMB) (Lagacé, 2010)

Thirty-five single-syllable words were presented monaurally at 60 dB HL in the presence of an 8-talker babble noise at 55 dB HL in the same ear. The child is instructed to repeat each word presented. A percentage of correct responses is calculated.

1.2. Gaps in Noise Test (GIN) (Shinn et al., 2009)

Each ear was tested separately at 50 dB HL. Four lists were available for this test, and between 29 and 36, six-second noise segments were presented to each ear. Each noise segment was interrupted between one and three times. There were 60 interruptions and nine different durations of interruptions: 2, 3, 4, 5, 6, 8, 10, 15, or 20 msec. Sometimes, there was no interruption in the segment. The child was instructed to press a button each time they noticed an interruption. The threshold is calculated as the shortest perceived interruption duration with at least four out of six presentations identified, and all longer interruption durations were also identified at least four out of six times. The percentage of identified interruptions was also calculated.

1.3. Pitch Pattern Sequence Test (PPST) (Musiek, 1994)

Fifteen or thirty groups of a three-sound sequence including two different types of sound – high (1122 Hz) and low (880 Hz) – were administered at a 50 dB sensation level (SL) of the threshold at 1000 Hz for each ear. The child was instructed to listen to each sequence and give a verbal label for each sequence (ex., high-low-high). For the same test, children who failed the verbal labelling were instructed to listen to 15 or 30 more sequences in each ear and hum the sequence heard. A percentage of correct responses was calculated.

1.4. Duration Pattern Sequence Test (DPT) (Musiek, 1994)

This test was administered at a 50 dB sensation level (SL) of the threshold at 1000 Hz monaurally and included 15 or 30 sequences of three sounds. Two types of sounds, short (250 msec) and long (500 msec), were presented, and children were instructed to listen,

identify and name each sequence correctly (ex., long-long-short). A percentage of total correct responses per ear was calculated.

1.5. Masking Level Difference (MLD) (Lynn et al., 1981)

Children were presented with a binaural narrow band noise around 500 Hz at a level of 60 dB HL. In that noise, a threshold search (Carhart & Jerger, 1959) was conducted with a 500 Hz pulsating pure tone. The child was required to press a button each time they heard the pure tone. Two different conditions were used: a more challenging condition where both the signal (S) and the noise (N) were in phase (S0N0) in both ears and an easier condition where the signal phase was shifted by 180 degrees in one ear relative to the other, and the noise phase remained the same in both ears (SπN0). The difference between the thresholds of both conditions determined the degree of release from masking.

1.6. Écoute Dichotique de chiffres (EDC) (Jutras et al., 2012)

This test measured binaural integration. It involves sending two pairs of digits simultaneously to each ear twenty times. The four digits presented in each pair were all different. The child had to repeat the four presented digits. A percentage of correct digits identified was calculated in each ear.

2. Cognitive screening test descriptions (Gualtieri & Johnson, 2006)

2.1.Verbal Memory Test

This test consisted of three phases. Firstly, the participant had to memorize fifteen words on a computer screen, one at a time. Then, they were presented with a new list and had to identify the previously memorized words amongst new words. Lastly, they had to identify them again at the end of the screening test, about twenty to thirty minutes later.

2.2. Visual Memory Test

This test was conducted in the same three-phase manner as the Verbal Memory Test but with fifteen geometric shapes instead of words.

2.3. Finger Tapping Test

In this test, the participant had to press the space bar on a computer keyboard with their index fingers as fast and as many times as possible in 10 seconds. They did it seven times, once for practice, followed by three trials with each index finger.

2.4. Symbol-Digit Coding Test

In the current subtest, two tables, each with two rows and eight columns, were presented on the screen. In the top table, the first row contains eight symbols, each associated with a number from 2 to 9. In the second table, only the symbols were present in a random order. The child had to enter as precisely and as many corresponding numbers to the symbols in two minutes.

2.5. Stroop Test

The Stroop Test consisted of three parts. In the first part, the words RED, YELLOW, BLUE, and GREEN appeared in black, randomly presented on the computer screen. The child had to press the space bar as soon as they saw the word. The same words were presented in colour on the screen in the second part. The child had to press the space bar only when the colour of the word and the word matched. For the third part, the child pressed the space bar only when the colour of the word did not match the word.

2.6. Divided Attention Test

This test measured the participant's ability to follow randomly changing instructions as they had to match geometric objects by shape or colour. Squares and circles appeared on the screen in blue or red, one at the top and two at the bottom. The figure at the top is either a red or blue square or a circle, while those at the bottom are either or both red or blue squares or circles. One of two rules will appear: "Match the colour" or "Match the form", and the participant must match the correct bottom shape or the colour with the top one.

2.7. Continuous Performance Test

In this test, letters appear on the computer screen one at a time. Participants must press the space bar on the keyboard only when and every time they see the letter "B." The letters are presented randomly for five minutes.

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CHAPTER 3. Electrophysiological experiment

3.1. Aims

This chapter aims to answer the third and fourth aims of the current thesis which was to provide information relating to the identification of a neurophysiological marker of auditory dysfunction following mTBI in children and if it changes over time. It is composed of three scientific articles. This investigation was the subject of Article 4 while Articles 2 and 3 circumscribe the data coming from the pre-experiment.

3.2. Pre-experiment

3.2.1. Methodology

Article 2 and Article 3 represent the pre-experiment in the electrophysiological measure (see Figure 4, Chapter 1. Introduction, p.17). These two pre-experimental studies investigated parameter modulation of AEPs (Article 2) and Time-Frequency analysis (Article 3) in 15 typically developing children and 15 adults in order to select the appropriate parameters for the investigation of auditory processing in quiet and in noise with mTBI children. In Article 2, ALRs (P1, N1, P2, N2) were investigated at one electrode (Cz) with the modulation of three main recording parameters, type of stimulus, type of noise and signal to noise ratio (see 60 to 63 for specific methodology). In Article 3, with the same recordings, time frequency analysis was explored. Both phase and power related analysis were investigated in three electrodes (T7, Cz and T8) (see 112 to 117 for specific methodology).

3.2.2. Article 2

Article 2, in the following form, was published in *Neuroscience* in 2024.

Duquette-Laplante, F., Jutras, B., Néron, N., Fortin, S., & Koravand, A. (2024). Exploring the Differences Between an Immature and a Mature Human Auditory System Through Auditory Late Responses in Quiet and in Noise. *Neuroscience*, *545*, 171-184. https://doi.org/10.1016/j.neuroscience.2024.03.018

Title

Exploring the differences between an immature and a mature human auditory system through auditory late responses in quiet and in noise

Author names and affiliations

Fauve Duquette-Laplante [a,b,c], Benoît Jutras [b,c], Noémie Néron[b,c], Sandra Fortin[b] & Amineh Koravand[a]

a. Audiology and Speech Pathology Program, School of Rehabilitation Sciences, University of Ottawa, Roger Guindon Hall, 451 Smyth Road, Room 3071, Ottawa, Ontario, Canada, K1H 8M5

b. School of Speech-Language Pathology and Audiology, Université de Montréal, c.p. 6128, succ. Centre-ville, Montréal, Canada, H3C 3J7

c. Research Center, CHU Sainte-Justine, 3175, Côte Sainte-Catherine, Montréal, Québec, Canada, H3T 1C5

Corresponding author

Fauve Duquette-Laplante, Audiology and Speech Pathology Program, School of Rehabilitation Sciences, University of Ottawa, Roger Guindon Hall, 451 Smyth Road, Room 3071, Ottawa, Ontario, Canada, K1H 8M5

Declaration of interest

The authors have declared that no conflict of interest existed at the time of publication.

Abstract

Children are disadvantaged compared to adults when they perceive speech in a noisy environment. Noise reduces their ability to extract and understand auditory information. Auditory-Evoked Late Responses (ALRs) offer insight into how the auditory system can process information in noise. This study investigated how noise, signal-to-noise ratio (SNR), and stimulus type affect ALRs in children and adults. Fifteen participants from each group with normal hearing were studied under various conditions. The findings revealed that both groups experienced delayed latencies and reduced amplitudes in noise but that children had fewer identifiable waves than adults. Babble noise had a significant impact on both groups, limiting the analysis to one condition: the /da/ stimulus at +10 dB SNR for the P1 wave. P1 amplitude was greater in quiet for children compared to adults, with no stimulus effect. Children generally exhibited longer latencies. N1 latency was longer in noise, with larger amplitudes in white noise compared to quiet for both groups. P2 latency was shorter with the verbal stimulus in quiet, with larger amplitudes in children than adults. N2 latency was shorter in quiet, with no amplitude differences between the groups. Overall, noise prolonged latencies and reduced amplitudes. Different noise types had varying impacts, with the eight-talker babble noise causing more disruption. Children's auditory system responded similarly to adults but may be more susceptible to noise. This research emphasizes the need to understand noise's impact on children's auditory development, given their exposure to noisy environments, requiring further exploration of noise parameters in children.

Keywords

Auditory Late Response, auditory system, hearing in noise, auditory processing, pediatric

1. Introduction

Listening in noise has a deleterious effect on communication. Whether in restaurants, schools or other places where people are surrounded by noise, communication is at risk of becoming arduous. Noise reduces the ability to extract and understand complete auditory information. Understanding speech in these situations relies mainly on knowledge and auditory processing abilities. Noise's impact on speech perception and listening comprehension was measured in classroom-like settings. Children perform significantly worse in such environments than adults on listening comprehension and speech perception tasks (Klatte et al., 2010). Children are disadvantaged compared to adults, as their auditory system is still developing towards reaching its most efficient form (Hall et al., 2002). Leibold et al. (2016) identified that 8- to 10-year-old children had poorer spondee word identification thresholds than adults for continuous and gaited two-talker and speech-shaped noises. These findings are aligned with those of Leibold and Buss's (2013) study comparing consonant identification in school-aged children (5 to 13 years old) and adults in two types of noise: speech-shaped and two-talker maskers. They reported that children under ten had more difficulty identifying the consonants in a speech-shaped noise than 11 to 13-year-olds and adults. In addition, all children's performances in a two-talker masker were weaker than adult performances. These results suggest that children's developing auditory system is less efficient than adults' in listening in noisy communication situations.

Moreover, other factors, such as fatigue (Key et al., 2017), attention (Thompson et al., 2017), and motivation Field (Silman et al., 2000), have been proven to modulate children's results on behavioural tasks. As opposed to behavioural tests, objective measures of the auditory system can offer help in understanding how information is processed in noise without being affected by behavioural components such as motivation or fatigue (Cacace & McFarland, 2005; Gyldenkærne et al., 2014; Hurley, 2018). Auditory-Evoked Late Responses (ALRs) provide deeper comprehension and understanding of the physiological characteristics and developmental trajectory of the auditory system (Ponton et al., 2000). ALRs, composed of four distinct sequential positive and negative peaks (P1, N1, P2 and N2), can be measured from early childhood through adulthood (Ceponiene et al., 2005; Gustafson et al., 2019; Ponton et al., 2000). They provide an opportunity to visualize the

neural representations of sound encoding at the cortical level (Picton et al., 1974). In adults, P1 is known to be generated in the secondary areas of the primary auditory cortex and is characterized by the early pre-perceptual processing of acoustic sound features (Ceponiene et al., 2005; Liégeois-Chauvel et al., 1994). N1, generated in the supratemporal cortex (Ceponiene et al., 2002; Vaughan & Ritter, 1970), is correlated with the behavioural detection threshold (Martin et al., 1999) and the sound onset features (Näätänen, 1990). P2 sourced at the supratemporal auditory cortex with the frontal and parietal cortices (Rif et al., 1991) represents the sound content feature encoding and modulation of the sensory stimulus information (Ceponiene et al., 2005). N2 is sound content feature processing and reflects largely perception-independent auditory processing (Perrault & Picton, 1984); it is elicited by the overall temporal lobe (Ceponiene et al., 2002). As the auditory system develops throughout childhood and early adolescence, the ALRs follow a maturation pattern (Ponton et al., 2000; Wunderlich et al., 2006). When elicited in young children, generally before age 9, ALRs are dominated by two wave components, P1 and N2, as they appear very early in their development (Ponton et al., 2000). With the child's growth, the N1-P2 complex develops, and an overall reduction of the latencies and amplitudes of the two initial waves, P1 and N2, can be observed (Ceponiene et al., 2005; Pang & Taylor, 2000; Ponton et al., 2000; Wunderlich et al., 2006). Such changes in wave components' amplitudes and latencies are helpful in understanding the changes occurring with the maturation of the central auditory system (Ponton et al., 2000; Wunderlich et al., 2006).

Studied extensively in adults, noise-evoked ALRs can be modulated through specific parameters, such as (1) the types of noise, (2) the ratio between the stimuli and the noise level (signal-to-noise ratio – SNR) and (3) the types of stimulus (Androulidakis & Jones, 2006; Billings et al., 2009, 2011; Gustafson et al., 2019; Maamor & Billings, 2017; Papesh et al., 2015; Small et al., 2018; Whiting et al., 1998). Those parameters are important when measuring auditory encoding in noise (Androulidakis & Jones, 2006; Billings et al., 2009, 2011; Gustafson et al., 2019; Maamor & Billings, 2017; Papesh et al., 2015; Small et al., 2018; Whiting et al., 1998). However, only a few studies investigated whether and how these specific parameters impact children's auditory system.

1.1. Types of noise

Androulidakis and Jones (2006) explored the effect of different noises on ALRs in adults. Results showed that wideband unmodulated masker noise had a more detrimental effect on sound (pure tone) processing than amplitude-modulated masker noise as latency was prolonged and amplitude was reduced for all ALR waves (Androulidakis & Jones, 2006). Billings et al.'s 2011 study also compared several noise types: continuous speech spectrum noise, interrupted speech spectrum noise, and four-talker babble noise. Results in adults revealed that the most reduced P1 and N1 latencies occurred in interrupted noise conditions, and the most prolonged latency took place with the four-talker babble noise (Billings et al., 2011). Furthermore, compared to continuous noise, four-talker babble noise decreased the N1 amplitude (Billings et al., 2011). For the other types of noise, such as the interrupted speech spectrum noise and wave components, such as P2, amplitude results were generally reduced but did not always reach significance (Androulidakis & Jones, 2006; Billings et al., 2011). Maamor and Billings (2017) compared three types of noise: a continuous speech-spectrum noise, a one-talker modulated noise and a four-talker babble noise. Findings demonstrated that the four-talker babble noise, which has variation in its temporal envelope and spectrum, resulted in the poorest waveforms in all SNRs, as the amplitudes were significantly decreased in adults. The latencies were significantly increased, especially on N1 and P2 wave components. No ALR studies compared the impacts of different types of noise on children's auditory system.

1.2. Signal-to-Noise Ratio

SNR was reported as the most influential parameter modulator when recording ALRs in adults and children (Anderson et al., 2010; Benítez-Barrera et al., 2021; Billings et al., 2009, 2013; Maamor & Billings, 2017; Papesh et al., 2015; Small et al., 2018; Whiting et al., 1998). Overall, findings in both populations are heterogeneous but mainly indicate that the more challenging the SNRs are, the longer latencies and smaller amplitudes are expected. In most recorded studies, P1 (Billings et al., 2009; Maamor & Billings, 2017; Papesh et al., 2015), N1 (Benítez-Barrera et al., 2021; Billings et al., 2009; Maamor & Billings, 2017; Papesh et al., 2015; Whiting et al., 1998), P2 (Benítez-Barrera et al., 2021;

Billings et al., 2009; Maamor & Billings, 2017; Papesh et al., 2015; Small et al., 2018), and N2 (Almeqbel & McMahon, 2015; Benítez-Barrera et al., 2021; Billings et al., 2009; Maamor & Billings, 2017; Papesh et al., 2015) latencies were elongated with the decrease of the SNR. Regarding the effect of SNRs on ALR amplitude, P1 (Anderson et al., 2010; Maamor & Billings, 2017; Papesh et al., 2015; Small et al., 2018) and P2 (Benítez-Barrera et al., 2021; Billings et al., 2009; Maamor & Billings, 2017; Papesh et al., 2015; Small et al., 2018) amplitudes increased systematically as a function of the SNR. N1 and N2 amplitude results were revealed to be more heterogeneous. N1 (Benítez-Barrera et al., 2021; Billings et al., 2009; Maamor & Billings, 2017; Small et al., 2018; Whiting et al., 1998) and N2 (Billings et al., 2009; Maamor & Billings, 2017; Papesh et al., 2015; Whiting et al., 1998) amplitudes were reduced in multiple studies with a smaller SNR. However, Papesh et al. (2015), using three conditions (quiet, +30 and +10 dB SNR), demonstrated that N1 amplitude was enhanced for both noise conditions, whereas N2 was only enhanced for the +30 dB SNR condition, suggesting a non-linear effect of noise relative level on these ALRs' components. Variability in results could partly be explained by the differences in protocols chosen to evaluate SNR modulation with studies using active versus passive paradigms, different stimuli, SNRs and types of noise.

1.3. Types of Stimulus

The types of stimulus can impact ALR wave components' magnitude and timing. In adults, verbal stimulation with quiet and noise speech sounds generally resulted in longer latency and larger amplitude for the N1-P2 complex than tone stimulation (Billings et al., 2011; Tiitinen et al., 1999). ALRs' peak latencies have been reported to be more sensitive to noise than amplitudes. Billings et al. (2011) recorded passive ALRs in normal-hearing young adults with two types of stimuli: verbal (/ba/) and nonverbal (1000 Hz pure tone). Four listening conditions were used: quiet, continuous noise, interrupted noise, and four-talker babble. The results reveal prolonged latency for P1, N1, and P2 peaks with the verbal stimulus compared to 1000 Hz pure tone in noise conditions, but there are no significant amplitude differences. No known ALRs studies compared tone and verbal evoked stimulation in noise among children. In quiet, types of stimuli were explored in children, and results revealed that the slope following the P1 waveform and the N2 peak were more

negative for the syllable when compared to the pure tone (Ceponiene et al., 2005). Similarly, Koravand et al. (2012, 2013) explored the difference between tone and verbal stimuli in children and reported extended latencies and lower amplitudes for the verbal compared to the tonal stimuli.

In summary, based on the mentioned studies, experimental parameter modulations affect ALRs in children and adults (Androulidakis & Jones, 2006; Billings et al., 2009, 2011; Gustafson et al., 2019; Maamor & Billings, 2017; Papesh et al., 2015; Small et al., 2018; Whiting et al., 1998). Overall, babble noise produced longer latency and smaller amplitude on ALR waveforms than those in white noise in adults (Billings et al., 2011). Wave latencies and amplitudes can vary as a function of the SNR (Benítez-Barrera et al., 2021; Billings et al., 2011; Maamor & Billings, 2017). Only one study directly compared adults' and children's ALRs elicited by noise (Gustafson et al., 2019). At a favourable +15 dB SNR, no significant differences were found between adults and children (Gustafson et al., 2019). This lack of difference in high SNRs, combined with behavioural studies showing that children under the most challenging conditions required higher SNRs than adults to process speech in noise, (Hall et al., 2002; Klatte et al., 2010; Leibold et al., 2016; Leibold & Buss, 2013) demonstrated the need for further investigation. Verbal stimuli also produced longer latencies and smaller amplitudes when compared to tonal stimuli in children (Koravand et al., 2012, 2013). Such results underline the need for further investigation of parameter modulation in children compared to adults to better understand the disruption that noise can inflict on children's ALRs.

1.4. Objectives

The main objective of this study was to explore the modulation of cortical sound encoding in noise in both children and adults. More specifically, this study aimed to investigate the effects of modulating the listening conditions (quiet and with noise), types of noise (eight-talker babble noise and white noise), SNR (+10, +5 and 0 dB) and types of stimulus (1000 Hz pure tone and verbal /da/), on ALRs wave components P1, N1, P2, and N2 in children when compared to adults. The present study was innovative because, with the same protocol and parameter modulation, no known study has yet evaluated if and how noise

can alter immature auditory systems differently than mature auditory systems through ALRs. With multiple parameter modulations come multiple hypotheses: (1) a reduction of the amplitudes and an elongation of latencies between quiet and noise conditions as a function of the SNR and types of stimulus (Benítez-Barrera et al., 2021; Billings et al., 2011; Koravand et al., 2012, 2013; Maamor & Billings, 2017); (2) a more significant impact of the babble noise when compared to the white noise (Billings et al., 2011; Maamor & Billings, 2017); and (3) in line with behavioural studies (Leibold et al., 2016; Leibold & Buss, 2013), children's ALRs in both latency and amplitude will be affected to a greater extent in most unfavourable conditions than adults. Results of this study could provide more insights into the differences and similarities of the mechanisms involved in auditory processing in noise in children and adults.

2. Methods

The CHU Sainte-Justine Research Ethics Board approved this study. All adult participants and legal guardians received and signed a copy of the written consent form. Children's assent was obtained before the beginning of the study.

2.1. Participants

Fifteen young adults (mean age: 24.50 ± 1.59 years; 22 to 27 years; twelve women) and fifteen children (mean age: 9.90 ± 1.35 years; 8 to 12 years; four girls) whose first language was French participated in the study. Participants with any of the following conditions were excluded from the present study: hearing thresholds ≥ 15dBHL at any frequency from 250 to 8000Hz, history of significant otologic problems such as chronic otitis media, taking or having a history of ototoxic medication, congenital, neurological, developmental, or metabolic disorders, a diagnosis of intellectual disability, and those born prematurely (< 37 weeks).

2.2. Procedures

The research project took place at the École d'orthophonie et d'audiologie of the Université de Montréal. For each participant, the data collection lasted about two hours and 30 minutes

and comprised the evaluation of the peripheral auditory system and electrophysiological recordings.

2.2.1. Peripheral auditory evaluation

An extensive peripheral auditory evaluation was conducted in both ears with each participant: visualization of the external ear canals, and measurements of the middle ear function, the ipsilateral and contralateral stapedial reflex thresholds at four frequencies: 500, 1000, 2000 and 4000 Hz (GSI TympStar pro), as well as the distortion product otoacoustic emissions (DPOAEs) amplitude and SNR (Otodynamics ILO6) at seven frequencies: 1000, 1500, 2000, 3000, 4000, 6000 and 8000 Hz. In a sound-attenuated booth, tonal audiometry (Madsen Astera 2) at eight frequencies: 250, 500, 1000, 2000, 4000 and 8000 Hz and word recognition scores in a quiet were performed in each ear.

2.2.2. Electrophysiological measurements

2.2.2.1. Recording

The measurements were recorded with the software PyCorder (BrainVision, LLC) on a computer connected to the BrainVision actiCHAMP™ amplifier (BrainVision LLC). A cap with 64 Ag/AgCl electrodes was positioned on each participant's head according to the 10-20 system (Jasper, 1958; Klem, 1999). For each active electrode, an impedance of no more than 40 kΩ was obtained (Mathewson et al., 2017). The Oz electrode was selected as the online reference electrode. Vertical eye movements were recorded by electrodes located under and above the eyes. Horizontal eye movement was recorded with the adjacent frontotemporal electrodes. Participants were instructed to avoid movements as much as possible, ignore the sound stimulation when presented and watch a chosen muted movie with subtitles. Breaks were offered between blocks as needed by the participant.

Binaural insert earphones (E-A-RTONE 3A) were used to transmit stimuli, comprising of 2800 trials in two different conditions: 400 trials in silence and 2400 in noise. Auditory stimuli were presented through a computer with the Presentation® software (Neurobehavioral Systems Inc.) via an audiometer (Madsen, Midimate 602). The auditory stimulation was separated into fourteen blocks of 200 presentations; each had an

approximate duration of four minutes and 15 seconds. The Pratt synthesizer Field created a syllable /da/ and a 1000 Hz pure tone for the experiment (Boersma & Weenink, 1992). For both stimuli, the duration was 170 msec with a rise and a fall time of 10 msec. Both stimuli were calibrated with a sonometer (Larson Davis Laboratories model 800B) to an output of 70 dBA. The interstimulus interval was a random jitter with a duration between 1130 and 1330 msec. The acquisition window (epoch) was set from -200 to 800 msec. Two types of noise were employed: white noise generated with the Audacity® software (Audacity Team, 1999) and an eight-talker Canadian French babble noise (Lagacé, 2014). Calibrated with the sonometer, both noise types were elicited at three SNRs: +10, +5 and 0 dB. The order of the fourteen stimuli conditions was randomized between participants.

2.2.2.2. Pre-processing

The EEG signal was analyzed in MATLAB version 2022b (The MathWorks Inc., 2022) with Fieldtrip (Oostenveld et al., 2010). EEG segments with an amplitude exceeding ± 100 μV were not included in the average data to exclude artifacts. After removing these EEG segments, the remaining segments were corrected with the Independent Component Analysis (ICA) method (Makeig et al., 1993) to extract eye movements from the signal. EEG data was filtered with a lowpass filter of 30 Hz and a baseline window of -200 to 0 msec and then averaged over each condition.

ALR components (P1, N1, P2, N2) were identified by two independent judges according to a time window that varied according to the listening conditions. The identification was based on two rules: (1) the most negative or positive wave component in the predetermined time windows based on previous studies (Benítez-Barrera et al., 2021; Gustafson et al., 2019) and on grand average waveforms – P1: children 40-290 ms, adults: 50-170 ms; N1: children 100-300 ms and adults: 100-250 ms; P2: children 160-360 ms, adults: 150-350 ms; N2: children 250-450 ms and adults: 230-460 ms, and (2) challenging identification was completed according to related ALRs (same stimuli and noise type). If discrepancies occurred, a discussion between judges took place to reach an agreement. The inter-judge validity was 88% and 85% for the total adults' and children's wave components, respectively.

2.3. Statistical Analysis

For some experimental conditions, not all ALR waves were identifiable. After wave identification, wave components for each of the fourteen experimental conditions with more than 3 (>20%) participants missing in either the children's or the adults' groups were excluded from the analysis. In the conditions where three or fewer participants did not have identifiable wave components, the group average was calculated to provide a value to the missing wave components. Repeated measures analyses of variance (ANOVA) were performed with IBM SPSS Statistics (Version 27). A three-level analysis was conducted by controlling for the effect of the independent factors of Group (children, adults), Listening condition (quiet, noise at specific SNRs), and Stimulus (syllable /da/, 1000 Hz pure tone) on the latency and amplitude of the ALRs wave components. The threshold of significance was delineated at $p<0.05$. For post-hoc t-test analyses, a Bonferroni correction factor was applied.

3. Results

The percentages of the presence of wave for all fourteen conditions in both groups were compiled in Table 1. Three to eight conditions could not be part of the analysis because wave components were absent for more than 20% of the participants in either group. In total, seven conditions for P1, five conditions for N1, and six conditions for P2 and N2 were included in the statistical analysis. These conditions mainly were quiet and white noise. Only one condition for the P1 wave component could be analyzed in babble noise: /da/ at +10 dB SNR.

Table 1. Percentage of the presence of each wave component (P1, N1, P2 and N2) for each group (adults and children) in all fourteen conditions.

		Quiet		Babble noise						White noise					
				+10 dB SNR		+5 dB SNR		0 dB SNR		+10 dB SNR		+5 dB SNR		0 dB SNR	
		1000 Hz	/da/	1000 Hz	/da/	1000 Hz	/da/	1000 Hz	/da/	1000 Hz	/da/	1000 Hz	/da/	1000 Hz	/da/
P1	Adult	100	100	87	93	87	60	53	47	100	87	93	93	80	93
	Child	100	93	60	80	47	27	27	0	87	100	73	93	67	80
N1	Adult	100	100	80	87	80	67	47	40	100	100	93	93	93	93
	Child	93	93	47	60	47	33	27	0	73	80	73	80	53	53
P2	Adult	93	100	67	67	60	60	33	33	93	100	87	93	80	93
	Child	93	93	47	40	47	20	27	0	93	87	87	80	60	67
N2	Adult	93	100	60	53	47	60	27	40	93	100	80	80	60	73
	Child	100	100	60	67	47	20	27	0	100	100	93	100	87	93

In gray are the conditions not retained for analysis (where the wave component was absent for more than three participants in the group).

After wave identification and elimination of the conditions that did not meet the criteria for further analysis, repeated-measures ANOVAs (see Table 2) and, when necessary, t-tests were performed on the analyzable conditions' latencies (see Figure 1) and amplitudes (see Figure 2).

Table 2. Repeated measures ANOVA results for each wave component (P1, N1, P2 and N2) for both dependant variables (latency and amplitude) in all analyzable conditions.

	Latency					Amplitude				
	df (between groups)	df (within groups)	F	p	η^2	df (between groups)	df (within groups)	F	p	η^2
P1										
(1) /da/ and 1000 Hz in quiet and white noise at +10 dB SNR for both groups										
Listening Condition (LC)	1	28	33.179	< .001	0.542	1	28	9.910	0.004	0.261
Stimulus (S)	1	28	0.098	NS	0.003	1	28	2.830	NS	0.092
Group (G)	1	28	17.460	< .001	0.384	1	28	13.090	0.001	0.319
LC × S	1	28	3.285	NS	0.105	1	28	0.887	NS	0.031
LC × G	1	28	2.036	NS	0.068	1	28	0.029	NS	0.001
S × G	1	28	0.072	NS	0.003	1	28	1.133	NS	0.039
LC × S × G	1	28	0.103	NS	0.004	1	28	3.473	NS	0.110
(2) /da/ in quiet and white noise at +10, +5, 0 dB SNR for both groups										
Listening Condition (LC)	1.7	48.3	38.946	< .001	0.582	3	84	0.784	NS	0.027
Group (G)	1	28	35.459	< .001	0.559	1	28	12.107	0.002	0.302
LC × G	1.7	48.3	1.845	NS	0.062	3	84	1.238	NS	0.042
(3) /da/ in quiet, white noise and babble noise at +10 dB SNR for both groups										
Listening Condition (LC)	1.54	43.04	41.890	< .001	0.599	2	56	3.028	NS	0.098
Group (G)	1	28	21.595	< .001	0.435	1	28	3.225	0.019	0.182
LC × G	2	56	0.350	NS	0.012	2	56	1.600	NS	0.054
N1										
(1) /da/ and 1000 Hz in quiet for both groups										
Stimulus (S)	1	28	0.499	NS	0.018	1	28	2.601	NS	0.085
Group (G)	1	28	4.396	0.045	0.136	1	28	14.833	< .001	0.346
S × G	1	28	1.292	NS	0.044	1	28	3.593	NS	0.114
(2) /da/ in quiet and white noise at +10 and +5 dB SNR for both groups										
Listening Condition (LC)	2	56	65.702	< .001	0.701	2	56	5.871	0.005	0.173
Group (G)	1	28	6.183	0.019	0.180	1	28	8.905	0.006	0.241
LC × G	2	56	1.906	NS	0.064	2	56	0.176	NS	0.006
P2										
(1) /da/ and 1000 Hz in quiet and white noise at +10 and +5 dB SNR for both groups										
Listening Condition (LC)	2	56	33.910	<.001	0.548	1.86	52.29	55.240	<.001	0.064
Stimulus (S)	1	28	47.273	<.001	0.628	2	56	0.454	NS	0.016
Group (G)	1	28	0.020	NS	0.001	1	28	86.235	<.001	0.755
LC × S	2	56	1.714	NS	0.058	2	56	11.244	<.001	0.287
LC × G	2	56	3.257	0.046	0.104	2	56	1.683	NS	0.057
S × G	1	28	6.556	0.016	0.190	1	28	9.870	NS	0.093
LC × S × G	2	56	6.556	0.041	0.108	2	56	2.550	<.001	0.154
N2										
(1) /da/ and 1000 Hz in quiet and white noise at +10 and +5 dB SNR for both groups										
Listening Condition (LC)	2	56	23.198	<.001	0.453	2	56	5.344	0.008	0.160
Stimulus (S)	1	28	26.754	<.001	0.489	1	28	66.114	<.001	0.702
Group (G)	1	28	0.014	NS	0.000	1	28	13.541	<.001	0.326
LC × S	2	56	0.462	NS	0.016	2	56	1.201	NS	0.041
LC × G	2	56	1.549	NS	0.053	2	56	7.981	<.001	0.222
S × G	1	28	0.010	NS	0.000	1	28	41.383	<.001	0.596
LC × S × G	2	56	0.004	NS	0.000	2	56	5.337	0.008	0.160

NS = non significant ($p > 0.05$)

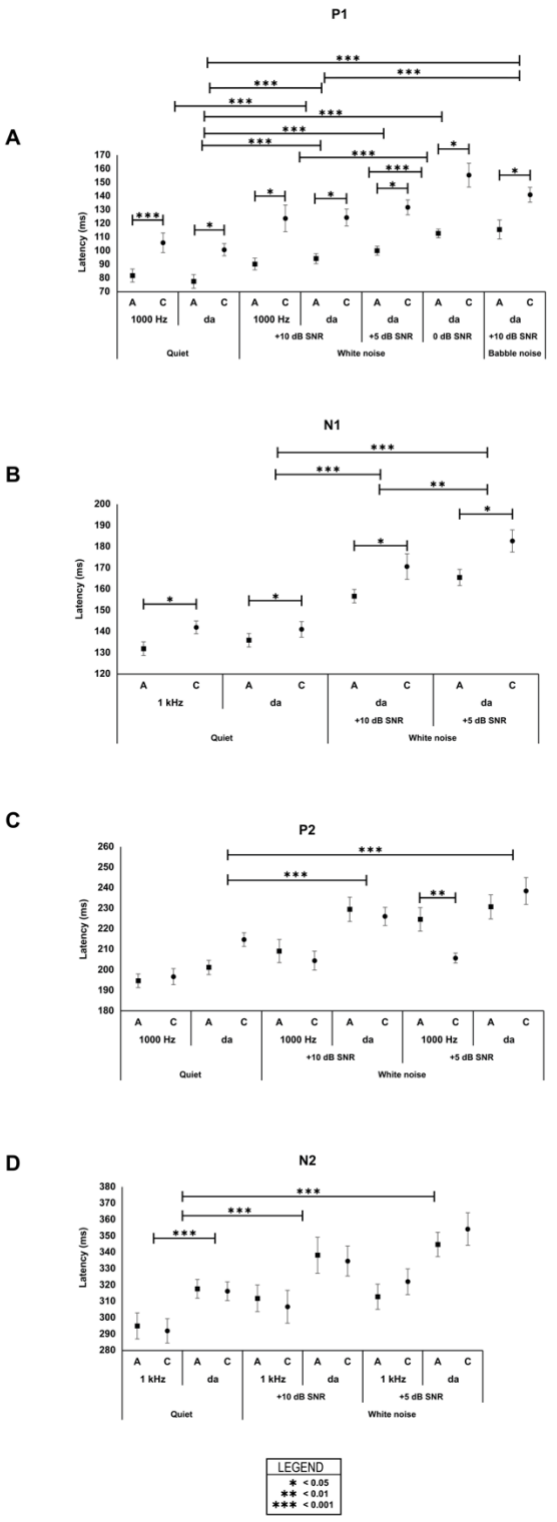

Figure 1. Average latency (and standard error) of P1(a), N1(b), P2 (c) and N2 (d) ALR's waveforms obtained in 15 adults (A) and 15 children (C) in quiet and in white noise at a signal-to-noise ratio of +10, +5 or 0 dB with the 1000 Hz pure tone and the syllable /da/.

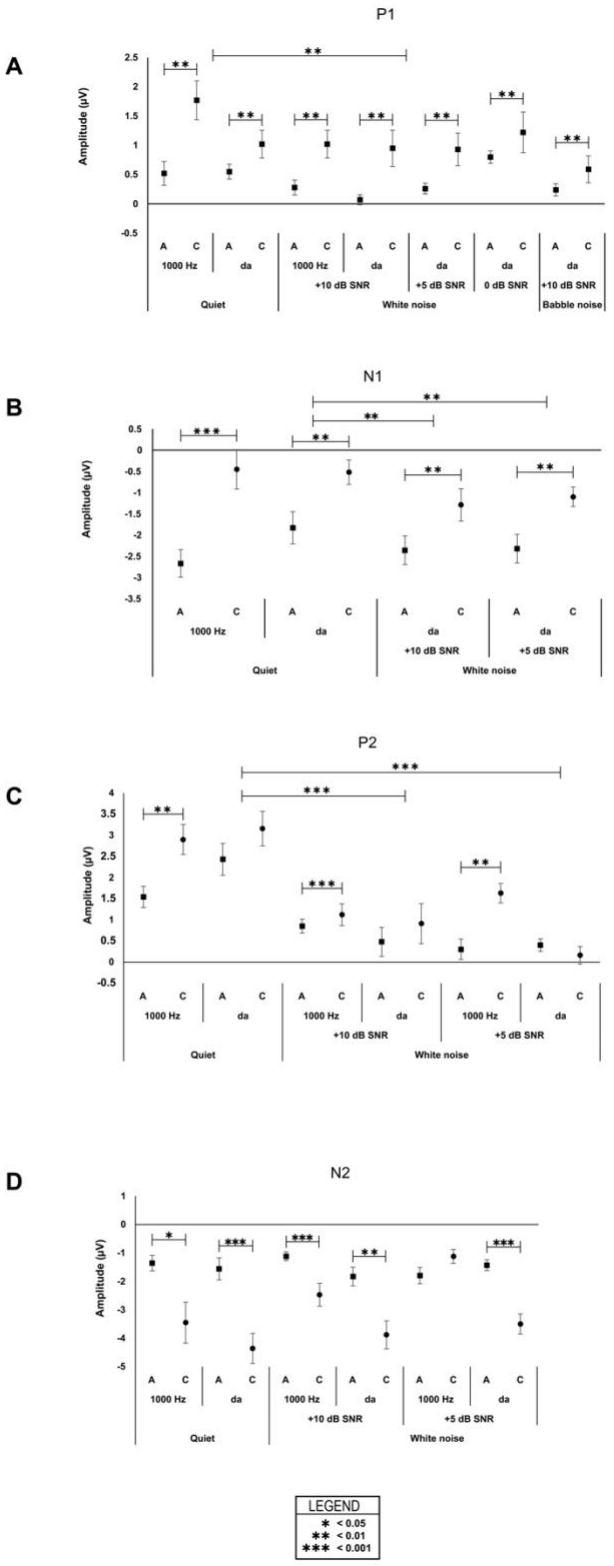

Figure 2. Average amplitude (and standard error) of P1(a), N1(b), P2 (c) and N2 (d) ALR's waveforms obtained in 15 adults (A) and 15 children (C) in quiet and in white noise at a signal-to-noise ratio of +10, +5 or 0 dB with the 1000 Hz pure tone and the syllable /da/.

3.1. P1

ANOVAs were performed on P1 latency (see Figure 1a) and amplitude (see Figure 2a) results according to a sequence of three ANOVAs for each dependent variable. A first ANOVA (1) was done with the syllable /da/ and the 1000 Hz pure tone stimuli in quiet and white noise at +10 SNR for the two groups. A second ANOVA (2) was performed with results obtained in the two groups with the syllable stimulus only in four listening conditions: quiet and white noise at +10, +5 and 0 SNRs. Finally, a third ANOVA (3) was done with the results of /da/ in quiet, babble, and white noise at +10 dB SNR.

3.1.1. Latency

In all three ANOVAs, the factor Group (1) [$F(1,28) = 17.46$, $p < 0.001$, $\eta^2 = 0.384$], (2) [$F(1,28) = 35.459$, $p < 0.001$, $\eta^2 = 0.559$] and (3) [$F(1,28) = 21.595$, $p < 0.001$, $\eta^2 = 0.435$] was significant, indicating that children had significantly longer P1 latencies than adults. With ANOVA (1), the two types of stimulus in quiet and in white noise at +10 dB SNR conditions, the factor Listening condition [$F(1,28) = 33.179$, $p < 0.001$, $\eta^2 = 0.542$] was also significant. In all participants, longer latencies were observed at +10 dB SNR when compared to the quiet condition. With ANOVA (2), /da/ in quiet and in white noise at +10, +5 and 0 dB SNR conditions, results revealed a significant effect of Listening condition [$F(1.7,48.3) = 38.946$, $p < 0.001$, $\eta^2 = 0.582$]. T-test results with Bonferroni correction revealed a significantly longer P1 latency in white noise at +10 dB SNR [$T(29) = -6.718$, $p < 0.001$], at +5 dB SNR [$T(29) = -6.377$, $p < 0.001$] and at 0 dB SNR [$T(29) = -7.437$, $p < 0.001$] compared to the quiet condition. It was also significantly longer in white noise at 0 dB SNR compared to +10 dB SNR [$T(29) = -5.138$, $p < 0.001$] and to +5 dB SNR [$T(29) = -5.618$, $p < 0.001$]. There was no significant difference between the listening condition with white noise at +10 dB SNR and the one at +5 dB SNR [$T(29) = -1.896$, $p > 0.008$]. In ANOVA (3) with /da/ in quiet, in white and babble noise at +10 SNR for the two groups, there was a significant difference for the factor Listening condition [$F(1.54,43.04) = 41.890$, $p < 0.001$, $\eta^2 = 0.599$]. T-test results with Bonferroni correction showed a significant difference between quiet and white noise [$T(29) = -6.718$, $p < 0.001$], quiet and babble noise [$T(29) = 8.896$, $p < 0.001$] and white noise and babble noise [$T(29) = 3.778$,

$p < 0.001$]. P1 latency was significantly longer in babble than in white noise and in white noise than in quiet.

3.1.2. Amplitude

P1 amplitude was greater for children than adults. The factor Group was significant in all three ANOVAs (1) [$F(1,28) = 13.09$, $p = 0.001$, $\eta^2 = 0.319$], (2) [$F(1,28) = 12.107$, $p = 0.002$, $\eta^2 = 0.302$], (3) [$F(1,28)= 3.225$, $p = 0.019$, $\eta^2 = 0.182$]. Results showed that in ANOVA (1), the two types of stimuli under quiet and white noise +10 dB SNR conditions for the two groups, the factor Listening condition [$F(1,28) = 9.91$, $p = 0.004$, $\eta^2 = 0.261$], had a significant effect on P1 amplitude. The amplitude was significantly greater in quiet than in white noise.

3.2. N1

Two ANOVAs were performed. One ANOVA (1) was performed with the results with the syllable /da/ and the 1000 Hz pure tone stimulation in quiet for the two groups. A second ANOVA (2) was done with the results obtained for the two groups with /da/ in quiet and in white noise at +10 and +5 SNR. Both ANOVAs were applied for the two dependent variables, N1 latency (see Figure 1b) and amplitude (see Figure 2b).

3.2.1. Latency

In both ANOVAs, the quiet condition with verbal and tonal stimulations for the two groups and /da/ in quiet and in white noise at +10 and +5 SNR for the two groups, a significant effect of Group (1) [$F(1,28)=4.396$, $p = 0.045$, $\eta^2 = 0.136$], (2) [$F(1,28) = 6.183$, $p = 0.019$, $\eta^2 = 0.18$] was obtained. N1 latency was longer in the children than in adults. With /da/ in quiet and in white noise at +10 and +5 SNR for the two groups, results revealed that the factor Listening condition [$F(2,56) = 65.702$, $p < 0.001$, $\eta^2 = 0.701$] was significant. T-test results with Bonferroni correction showed that N1 latency was significantly affected by the listening condition when comparing quiet and white noise at +10 dB SNR [$T(29) = -9.783$, $p < 0.001$], quiet and white noise at +5 dB SNR [$T(29) = -10.435$, $p < 0.001$] and white noise at +10 dB and +5 dB SNR [$T(29) = -2.860$, $p = 0.008$]. Latency values increased with decreasing SNR.

3.2.2. Amplitude

In both ANOVAs, in the quiet condition with /da/ and pure tone stimulation for the two groups and /da/ in quiet and in white noise at +10 and +5 SNR for the two groups, results showed a significant effect of Group (1) [$F(1,28) = 14.833$, $p < 0.001$, $\eta^2 = 0.346$], (2) [$F(1,28) = 8.905$, $p = 0.006$, $\eta^2 = 0.241$] on N1 amplitude, with greater values in the group of adults than in the group of children. With /da/ in quiet and in white noise at +10 and +5 SNR for the two groups, a significant effect of Listening condition [$F(2,56) = 5.871$, $p = 0.005$, $\eta^2 = 0.173$] was observed. T-test results with Bonferroni correction revealed that N1 amplitude was significantly lower in quiet than in white noise at +10 dB SNR [$T(29) = 2.820$, $p = 0.009$] and at +5 dB SNR [$T(29) = 2.960$, $p = 0.006$]. There was no significant difference between +10 and +5 dB SNR [$T(29) = -0.63$, $p > 0.017$].

3.3. P2

An ANOVA was carried out with the results obtained for the two groups with the pure tone and with the syllable /da/, in quiet and in white noise at +10 and +5 SNR, for P2 latency (see Figure 1c) and then for P2 amplitude (see Figure 2c).

3.3.1. Latency

Results of /da/ and 1000 Hz in quiet and in white noise +10 and +5 dB SNR for the two groups showed that Listening condition [$F(2,56) = 33.910$ $p < 0.001$, $\eta^2 = 0.548$], Stimulus [$F(1,28) = 47.273$, $p < 0.001$, $\eta^2 = 0.628$], Stimulus X Group [$F(1,28) = 6.556$, $p = 0.016$, $\eta^2 = 0.19$], Listening condition X Group [$F(2,56) = 3.257$, $p = 0.046$, $\eta^2 = 0.104$] and Listening condition X Stimulus X Group [$F(2,56) = 6.556$, $p = 0.041$, $\eta^2 = 0.108$] interactions had a significant effect on P2 latency.

The Listening condition X Group X Type of stimulus interaction was decomposed. With the pure tone, a significant effect of Listening condition [$F(2,56) = 16.842$, $p < 0.001$, $\eta^2 = 0.376$] and of Listening condition X Group interaction [$F(2,56) = 5.006$, $p = 0.01$, $\eta^2 = 0.152$] were found. However, the effect of Group [$F(1,28) = 1.885$, $p > 0.05$, $\eta^2 = 0.063$] was not significant. T-test results with Bonferroni correction showed a significant difference between adults and children in white noise at +5 dB SNR [$T(14) = 3.146$, $p =$

0.004], the latency being greater in adults than in children. No difference was shown between the two groups in quiet [T(14) = -0.403, p > 0.016] and in white noise at +10 dB SNR [T(14) = 0.697, p > 0.016]. With the syllable /da/, results revealed that the Listening condition [F(2,56) = 22.400, p < 0.001, η^2 = 0.444] was significant, but not the factor Group [F(1,28) = 1.167, p > 0.05, η^2 = 0.040] nor the Listening condition X Group interaction [F (2,56) = 2.173, p > 0.05, η^2 = 0.072]. Results from t-tests with Bonferroni correction showed shorter P2 latency in quiet than in white noise at +10 dB SNR [T(29) = -4.942, p < 0.001] and +5 dB SNR [T(29) = -6.821, p < 0.001]. There was no significant difference between the results in white noise at + 10 and +5 dB SNR [T(29) = -1.460, p > 0.016].

3.3.2. Amplitude

With /da/ and the pure tone in quiet and in white noise +10 and +5 dB SNR for the two groups, significant effects of Listening condition [F(1.86,52.29) = 55.24, p < 0.001, η^2 = 0.064] and Group [F(1,28) = 86.235, p < 0.001, η^2 = 0.755] were measured on P2 amplitude. The Listening condition X Stimulus [F(2,56) = 11.244 p < 0.001, η^2 = 0.287] and Listening condition X Stimulus X Group F(2,56) = 2.550, p < 0.001, η^2 = 0.154] interactions were also significant.

The interaction Listening Condition X Stimulus X Group was decomposed. With the pure tone, significant effects of Listening Condition [F(2,56) = 21.215, p < 0.001, η^2 = 0.441] and of Group [F(1,28) = 14.786, p < 0.001, η^2 = 0.346] were measured. The Listening condition X Group interaction [F(2,56) = 4.029, p = 0.023, η^2 = 0.126] was significant. The decomposition of the interaction showed greater amplitude in the group of children than in the group of adults in quiet [T(14) = -3.567, p = 0.003], in white noise at +10 dB SNR [T(14) = -6.212, p < 0.001] and +5 dB SNR [T(14) = -4.123, p = 0.001]. With the syllable /da/, results revealed that the Listening condition [F(2,56) = 55.412, p < 0.001, η^2 = 0.664] was significant, but not the factor Group [F(1,28) = 0.587, p > 0.05, η^2 = 0.021] and the Listening condition X Group interaction [F(2,56) = 3.897, p > 0.05, η^2 = 0.063]. T-test results with Bonferroni correction showed a greater amplitude with the syllable /da/ in quiet than in white noise at +10 dB SNR [T(29) = 8.37, p < 0.001) and at +5 dB SNR [T(29) =

9.525, $p < 0.001$]. There was no significant difference between the Listening condition factor at +10 and +5 dB SNR [$T(29) = 1.548$, $p > 0.017$].

3.4. N2

For N2 latency (see Figure 1d) and amplitude (see Figure 2d), one ANOVA was done from the results obtained in the two groups with the 1000 Hz pure tone and the syllable /da/ in quiet and in white noise at +10 and +5 SNR.

3.4.1. Latency

In quiet and in white noise at +10 and + 5 dB SNR for the two types of stimuli and the two groups, results showed significant effects of Listening condition [$F(2,56) = 23.198$, $p < 0.001$, $\eta^2 = 0.453$] and Stimulus [$F(1,28) = 26.754$, $p < 0.001$, $\eta^2 = 0.489$] on N2 latency. Results from t-tests with Bonferroni correction showed that N2 latency was significantly shorter in quiet than in white noise at +10 dB SNR [$T(29) = -4.815$, $p < 0.001$] and at +5 dB SNR [$T(29) = -7.219$, $p < 0.001$]. No significant difference in N2 amplitude was measured between white noise +10 and +5 dB SNR [$T(29) = -2.127$, $p > 0.017$]. The results also showed that the N2 latency was shorter with the 1000 Hz pure tone than the syllable /da/.

3.4.2. Amplitude

In quiet and in white noise at +10 and + 5 dB SNR for the two types of stimuli and the two groups, a significant effect of Listening condition [$F(2,56) = 5.344$, $p = 0.008$, $\eta^2 = 0.160$], of Stimulus [$F(1,28) = 66.114$, $p < 0.001$, $\eta^2 = 0.702$] and of Group [$F(1,28)= 13,541$, $p < 0.001$, $\eta^2 = 0.326$] was shown on N2 amplitude. The Listening condition X Group [$F(2,56) = 7.981$, $p < 0.001$, $\eta^2 = 0.222$], Stimulus X Group [$F(1,28) = 41.383$, $p < 0.001$, $\eta^2 = 0.596$] and Listening condition X Stimulus X Group [$F(2,56) = 5.337$, $p = 0.008$, $\eta^2 = 0.160$] interactions had a significant effect on N2 amplitude.

The Listening condition X Stimulus X Group interaction was decomposed by isolating Stimulus –1000 Hz and /da/. Results for the 1000 Hz revealed significant effects of Listening condition [$F(1.6,45.9) = 4.961$, $p = 0.016$, $\eta^2 = 0.151$], of Group [$F(1,28) = 4.658$,

$p = 0.04$, $\eta^2 = 0.143$], as well as of Listening condition X Group interaction [$F(2,56) = 11.004$, $p < 0.001$, $\eta^2 = 0.282$]. T-tests with Bonferroni correction showed that children had significantly greater amplitude than adults in quiet [$T(14) = 2.652$ $p = 0.019$], in white noise +10 dB SNR [$T(14) = 3.059$ $p = 0.008$], but not in white noise +5 dB SNR [$T(14) = -1.985$, $p > 0.017$]. Results from the second two-way ANOVA with /da/ showed that the factor Group [$F(1,28) = 23.655$, $p < 0.001$, $\eta^2 = 0.458$] had a significant effect on N2 amplitude but not the factor Listening condition [$F(2,56) = 1.951$, $p < 0.05$, $\eta^2 = 0.065$] nor the Listening condition X Group interaction [$F(2,56) = 1.349$, $p > 0.05$, $\eta^2 = 0.046$]. T-tests with Bonferroni correction showed that children have significantly greater amplitude than adults in quiet [$T(14) = 3.948$, $p = 0.001$], in white noise at +10 dB SNR [$T(14) = 3.494$, $p = 0.004$] and at +5 dB SNR [$T(14) = 4.249$, $p < 0.001$].

4. Discussion

The primary objective of this study was to understand the effect of types of noise, SNRs, and types of stimulus on ALRs' four-wave components – P1, N1, P2, and N2 – in children and adults. The main findings of this study include the marked differences in configuration between children's and adults' ALRs with the modulation of these three parameters. An average of 64% of identifiable waves in children compared to 78% in adults is in line with previous behavioural research indicating children are more affected by noise than adults (Hall et al., 2002; Klatte et al., 2010; Leibold et al., 2016; Leibold & Buss, 2013), but not with the electrophysiological study of Gustafson et al. (2019). They did not report differences between adults and children on ALRs' results in noise at +15 dB SNR. This could be explained by the testing protocol, as their recording conditions were more favourable than those of the current study. In the present study, smaller SNRs were used, and results showed that adults and children had different neurophysiological responses in noise as children's most resistant waves were P1 and N2. However, adults were P1 and N1 in babble noise and P1, N1 and P2 in white noise. N2 was more inhibited and less prominent in the quiet condition in adults than in children, which may explain its extinction in noise (Picton et al., 1974). The immaturity of the structures of the central auditory system may explain the difficulties of correctly processing information when overloaded with noise.

4.1. Types of noise

The type of noise did not have the same effect on the ALRs components. White noise was the most favourable noise condition. All three white noise conditions involving the verbal stimulus and two conditions involving the tone could be analyzed. Results are in line with the literature as, overall, the latency of the waveforms was significantly elongated, and the amplitude was considerably reduced in white noise than in quiet (Almeqbel & McMahon, 2015; Anderson et al., 2010; Androulidakis & Jones, 2006; Benítez-Barrera et al., 2021; Billings et al., 2007, 2009, 2011, 2013, 2015; Cunningham et al., 2001; Gustafson et al., 2019; Hayes et al., 2003; Kaplan-Neeman et al., 2006; Maamor & Billings, 2017; Papesh et al., 2015; Parbery-Clark et al., 2011; Whiting et al., 1998). The eight-talker babble noise affected wave morphology much more than the white noise (Figures 3 and 4). These findings mirrored Benitez-Berrera et al.'s (2021) study results. They found heavily altered waveform components with a four-talker babble noise at the +15 and +10 dB SNR. These results confirmed that babble noise is more disruptive than white noise. In the current study, P1 and N1 were barely identified, even in adults with this type of noise at the tested SNRs, except for P1 with /da/ at +10 SNR. P2 and N2 could not be identified in any babble conditions in at least twelve participants in both groups to be analyzed. These findings suggest that the structures of the central auditory system generating these waveforms were more affected by babble noise than those leading to the formation of the P1 waveform. This could point out that neural resources were allocated primarily to the structures engaged in the basic processing of sound features.

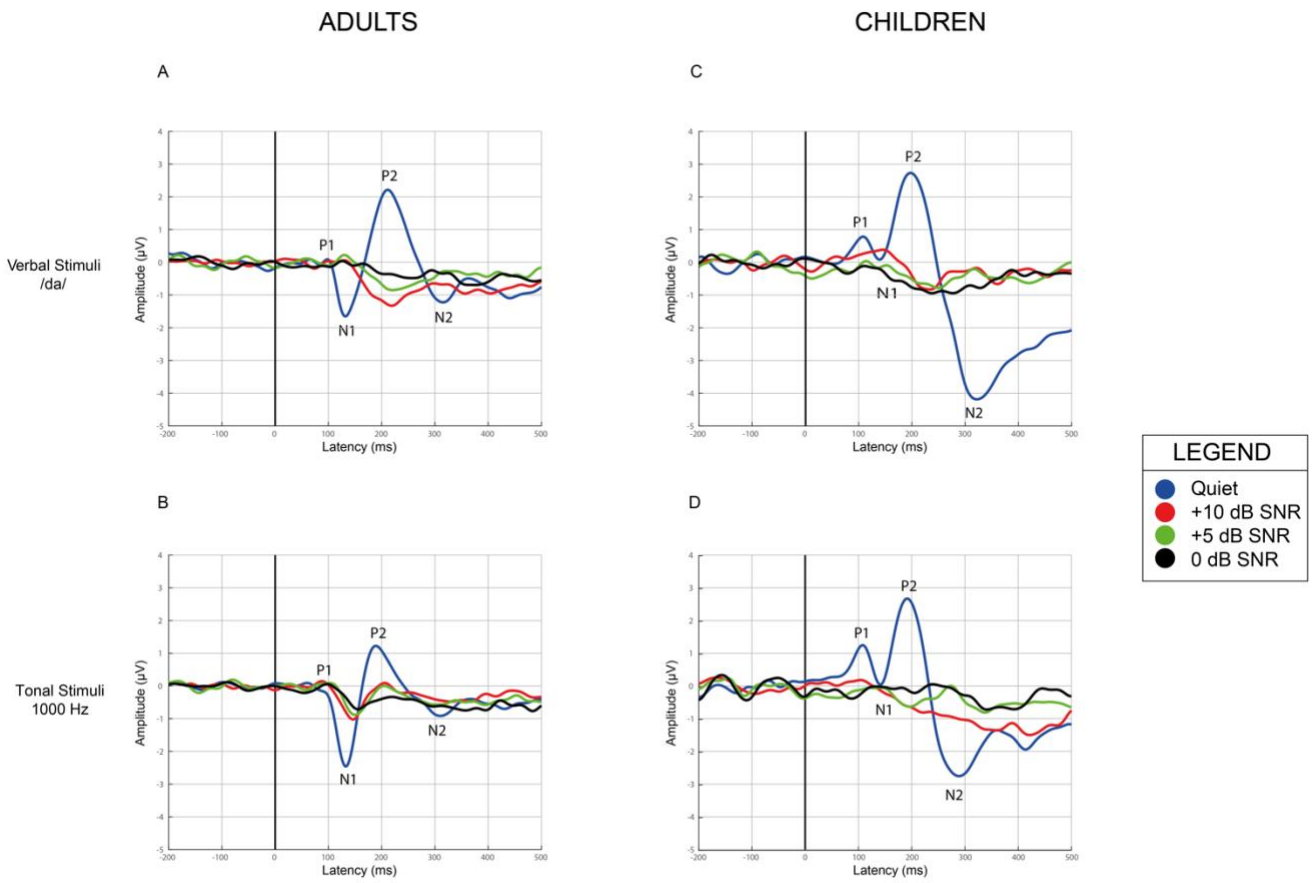

Figure 3. Grand average (Cz) in quiet and babble noise at +10, +5, 0 dB SNRs for the 15 adults with the verbal /da/ (A) and 1000 Hz pure tone (B) and the 15 children with the verbal /da/ (C) and 1000 Hz pure tone (D).

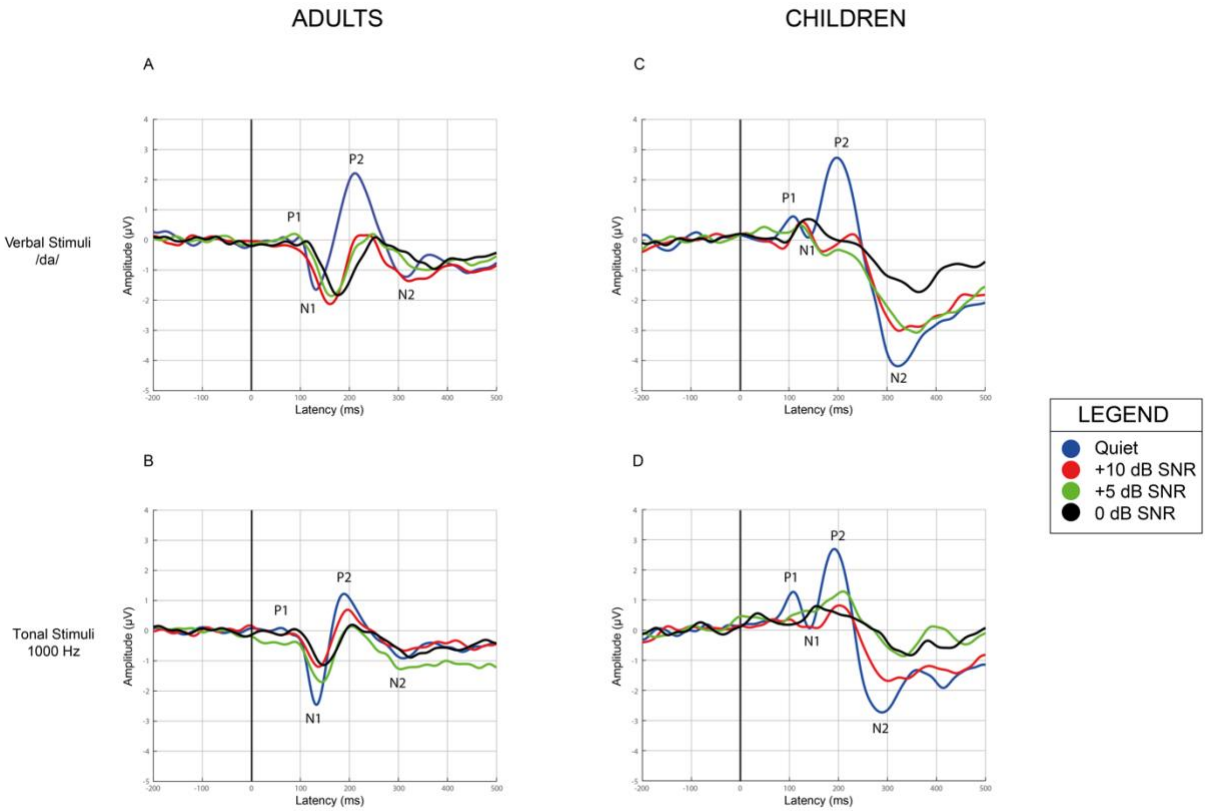

Figure 4. Grand average (Cz) in quiet and white noise at +10, +5, 0 dB SNRs for the 15 adults with the verbal /da/ (A) and 1000 Hz pure tone (B) and the 15 children with the verbal /da/ (C) and 1000 Hz pure tone (D).

In contrast, results from the studies of Billings et al. (2011) and Maamor and Billings (2017) showed that most of their recorded evoked potentials in babble noise had identifiable wave components. Inconsistencies between the studies could be due to protocol differences as these two studies utilized a babble noise of four talkers, and the current study used a babble noise with eight talkers. Maamor and Billings (2017) identified that while they found similarities between the effects of a speech-shaped noise and the babble noise, the variability and the more remarkable resemblance of the babble noise to the stimulation resulted in poorer waveforms. Moreover, results of behavioural studies have shown that a masking noise composed of eight talkers has a high level of informational and energetic masking.

In contrast, the masking noise of four speakers has a more informational than energetic masking effect (Rosen et al., 2013; Simpson & Cooke, 2005), making the 8-talker babble

the more efficient masker. Further investigation is required into the distinctions between the effect of informational/energetic masking and the spectral/temporal similarities between the babble noise and stimulation on electrophysiological recordings. Nonetheless, previous results and those of the present electrophysiological study support the idea that more ecologically relevant noise (closer to the stimulation) can have a more substantial destructive impact on auditory encoding when compared to continuous white noise.

4.2. SNR

In previous studies, the amplitude and latency of ALR components generally varied as a function of the SNR level (Benítez-Barrera et al., 2021; Billings et al., 2011; Maamor & Billings, 2017; Small et al., 2018; Whiting et al., 1998). This trend in ALR parameters was seen in the present study when the stimuli were masked by white noise, showing a significant reduction of the amplitude and a significant elongation of the latencies with decreasing SNR. Such an effect could not be seen in the listening conditions measured in babble noise. As previously stated, most babble noise conditions could not be analyzed due to a lack of identifiable waveforms. Therefore, observing the SNR effect on the amplitude and latency of the ALR components with the babble noise was almost impossible in both groups. However, children's central auditory system seemed more affected in the most challenging SNRs as the number of identified wave components was lower in children compared to adults (see Table 1).

4.3. Types of stimulus

ALR components were influenced by the types of stimulus. The verbal stimulus /da/ was in general more noise-resistant than the 1000 Hz pure tone for both groups, producing the highest percentage of identifiable waves in both types of noise for all SNRs (see Table 1). In the listening conditions where the two types of stimulus were identifiable, P1, P2 and N2 were generally more prominent, and N2 was significantly longer for the verbal condition. This has been repeated in studies as tonal stimuli responses seem more mature than verbal responses, explaining the significantly larger responses (Ceponiene et al., 2005; Ponton et al., 2000) and usually longer ALRs (Billings et al., 2011) for verbal stimulation than tonal stimulation in children. Children had significantly greater waves than adults in

the tonal condition but an absent P2 wave component at an SNR of 0 dB. N2 also demonstrated such an effect for the tonal stimuli, where children had significantly greater amplitudes than adults for both the quiet and the +10 dB SNR conditions but not significantly different for both groups at the +5 dB SNR condition. This effect was not recorded in the verbal conditions, as children's waves were significantly larger in all conditions. These results are similar to Billings et al.'s (2011) findings in adults, where the interaction between the spectral characteristics of the types of stimulus and the type of noise influenced the wave parameters. In the current study, the group (adults and children) and the types of stimulus (verbal and tonal) both interacted with the noise.

Unexpectedly, N1 amplitude was significantly more negative in white noise conditions (+10, +5 dB SNR) than quiet for the verbal stimulus for both groups. Such an increased negativity in noise was not recorded for the tonal stimulus. Results of a series of studies by Billings et al. (2007, 2009, 2011, 2013; 2016) and Mamoor and Billings (2017) did not show such an effect using verbal stimuli and similar noise. A few studies reported this phenomenon sparingly (Gustafson et al., 2019; Papesh et al., 2015). For example, Gustafson et al. (2019) found similar results where N1 was more negative in the noise condition in 7 to 10-year-old participants and not with older children or adults. They explained these findings by the incomplete maturation of the ALR components in quiet for these children (Gustafson et al., 2019). Such an explanation is not supported by the current study or by the results of Papesh et al. (2015), as both show larger N1 amplitude in noise than in quiet listening conditions with the verbal stimulus in adults. Papesh et al. (2015) offered another perspective on this phenomenon by proposing that the enhancement of N1 amplitude could be associated, in part, with the salience of the verbal stimulus with respect to the noise level. Such an effect was not possibly reproduced by the 1000 Hz pure tone in the white noise because this stimulus was easier to mask than the /da/. Its frequency is included in the combination of the frequencies composing the white noise, thus reducing the salience of the stimulus and, in turn, the N1 amplitude. Further research with different paradigms and parameter modulation is needed to understand such an effect, as its presence is not systematic.

In conclusion, the current study examined how parameter modulations with different types of noise, SNRs and types of stimulus can inform on the similarities and differences between adults' and children's sound encoding at a cortical level. Consistent with the reviewed literature, noise generally elongates latencies and reduces amplitudes in all noise conditions compared to quiet conditions. Results also showed that tones and speech stimuli are not equally noise-resistant and that an eight-talker babble noise was more disruptive than a white noise. The results revealed that the auditory system of children had similar responses but, due to its immaturity, seemed more impacted in processing auditory information in noise than adults. Understanding how children's auditory system are affected by noise is fundamental, as they spend a significant amount of time in noisy situations. Future research is needed to correctly identify the interactions between different noise parameter modulations in children and how they affect their immature auditory system.

5. Limitations of the study

While the current study provided valuable insights into the differences in auditory late responses (ALRs) between children and adults across diverse listening conditions, it is essential to consider certain limitations. One limitation of this study was sex, as it was not well-balanced between groups. There were a majority of women in the adult group but a minority of girls in the children's group. Such a difference could have influenced the results, as men and women can slightly differ in their auditory system function (Morlet et al., 1995; Roche et al., 1978; Tobias, 1965). The sample size, while sufficient for the optimal quiet conditions, was small, with only 15 participants in each group. Children generally had less identifiable wave components than adults, especially under the most adverse listening conditions. Statistical analysis could not include multiple conditions, almost completely removing the six conditions related to the babble noise as the wave components (P1-N1-P2-N2) were unidentifiable in many participants. The statistical analysis of the wave components in babble noise, when compared to the white noise, could have helped in better quantifying the differences between adults and children. In the group by condition interactions, there was a greater exclusion of P2 and N2 wave components than P1 and N1 wave components. Taken together with the presence of interactions primarily in conditions with higher SNRs and in the absence of such effects in lower SNR

conditions, it suggests the possibility of reduced statistical power in detecting group differences under more challenging listening conditions. Increasing participants in both groups could help to resolve this limitation. There were also limitations with the choice of parameter modulated. The eight-talker babble noise had a significant adverse effect on the wave components. The most challenging conditions, such as the babble noise with 0 dB SNR, produced little to no wave components in both groups. A future study with more favourable SNRs and a comparison with a four-talker babble noise and a spectral-matched continuous noise would help better understand the destructive effect of the eight-talker babble noise and better evaluate its impact on children's waves without the floor effect. The lack of behavioural measures in noise was also a limitation of this study, as it prevented the assessment of the relationship between the ALRs and those of behavioural results in noise with the same parameters.

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7. Data availability statement

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

8. Authors contributions

Fauve Duquette-Laplante: Conceptualization (equal); Data curation (lead); Formal Analysis (lead); Funding Acquisition (equal); Investigation (lead); Methodology (equal); Project administration (lead); Software (lead); Supervision (lead); Validation (lead); Visualization (lead); Writing - Original Draft Preparation (equal); Writing – review and editing (equal). Noémie Néron: Formal Analysis (supporting); Investigation (supporting); Writing - Original Draft Preparation (equal); Writing – review and editing (equal). Benoît Jutras: Conceptualization (equal); Formal Analysis (supporting); Funding Acquisition

(equal); Methodology (equal); Project Administration (supporting); Resources (equal); Supervision (lead); Validation (lead); Writing - Original Draft Preparation (equal); Writing – review and editing (equal). Amineh Koravand: Conceptualization (equal); Formal Analysis (supporting); Funding Acquisition (supporting); Methodology (equal); Project administration (supporting); Resources (equal); Supervision (lead); Writing - Original Draft Preparation (equal); Writing – review and editing (equal). Sandra Fortin: Investigation (supporting); Writing – review and editing (supporting).

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3.2.3. Article 3

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The impact of noise on auditory processing in children and adults: a time-frequency analysis perspective

Author names and affiliations

Fauve Duquette-Laplante[a,b,c], Aurélie Belleau-Matte[b,c], Boutheina Jemel[b,d], Benoît Jutras[b,c] & Amineh Koravand[a]

a. Audiology and Speech Pathology Program, School of Rehabilitation Sciences, University of Ottawa, Roger Guindon Hall, 451 Smyth Road, Room 3071, Ottawa, Ontario, Canada, K1H 8M5

b. School of Speech-Language Pathology and Audiology, Université de Montréal, c.p. 6128, succ. Centre-ville, Montréal, Canada, H3C 3J7

c. Azrieli Research Center, CHU Sainte-Justine, 3175, Côte Sainte-Catherine, Montréal, Québec, Canada, H3T 1C5

d. Research Laboratory in Neurosciences and Cognitive Electrophysiology, Research Center CIUSS-NIM, Hôpital Rivière des Prairies, 7070 Boul. Perras, Montréal, Québec, Canada, H1E 1A4

Corresponding author

Fauve Duquette-Laplante Audiology and Speech Pathology Program, School of Rehabilitation Sciences, University of Ottawa, Roger Guindon Hall, 451 Smyth Road, Room 3071, Ottawa, Ontario, Canada, K1H 8M5

Declaration of interest

The authors have declared that no conflict of interest existed at the time of publication.

Type of paper

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Abstract

Objective: The current study investigated the impact of listening conditions on cortical oscillatory activities in children and adults.

Experimental Procedure: Fifteen children and 15 adults participated in this study. Electrophysiological measures were recorded with 64 electrodes. Stimulation was presented binaurally with different parameters modulation: types of stimuli (tonal and verbal), listening conditions (in quiet and noise), types of noise (white and babble) and SNR (+10, +5 and 0). Intertrial phase clustering (ITPC) and power values were computed using spatially filtered data and complex Morlet wavelets. Data were statistically analyzed with mixed factorial ANOVAs.

Results: Children exhibited high phase and power values at the temporal electrodes, while adults showed high phase values and more negative power values at the central electrodes. Power values were significantly different between groups only in quiet conditions. Phase values were modulated by the different listening conditions, with the quiet condition being the easiest and the babble noise condition at 0 dB SNR being the most challenging.

Discussion: Findings supported literature regarding the maturational time course of auditory processing. Results also indicated that phase and power measures are sensitive to parameter modulation and could be used to understand auditory processing in noise, as they revealed increased susceptibility to noise in children compared to adults.

Keywords: Time-frequency analysis, auditory processing, noise, children, cortical oscillations

Abbreviations: SNR: signal-to-noise ratio; ALRs: Auditory-evoked late responses; ITPC: Intertrial phase clustering; HF: high frequency; LF: low frequency

1. Introduction

Speech perception in school-aged children is particularly vulnerable to the effect of noise (Elliott, 1979; Fallon et al., 2000; Jamieson et al., 2004; Talarico et al., 2007). The complex process of speech perception in noise, integral to childhood development, is influenced by sensory perception, linguistic abilities, and cognitive skills (Eisenberg et al., 2000; Elliott, 1979; Talarico et al., 2007). Fallon et al. (2000) observed that children generally underperform on speech in noise tasks compared to adults. Lower noise levels are necessary to achieve comparable performance in identifying sentence-ending words. The improvement in task performance with age is mainly due to cortical maturation, a process that extends into childhood and adolescence and is characterized by structural and functional changes in the central nervous system (Devous et al., 2006; Hallett & Proctor, 1996; Paus et al., 1997). This developmental phase involves synaptogenesis, increased myelination of nerve fibres and synaptic pruning, optimizing neural circuits and promoting developmental plasticity (Marsh et al., 2008; Paus et al., 1999; Whitford et al., 2007). Such plasticity is notable during childhood and adolescence in several brain regions, including the secondary auditory cortex (Devous et al., 2006; Gogtay et al., 2004; Paus et al., 1999). Throughout adolescence, electrophysiological responses to auditory stimuli provide compelling evidence for the ongoing refinement of auditory processing in the central auditory system in cortical and subcortical regions (Bishop et al., 2007; Cunningham et al., 2001; Ponton et al., 2000; Wunderlich et al., 2006). This complex interplay of maturational and neurophysiological changes highlights the dynamic nature of auditory processing during these crucial developmental stages. Such a process can be captured by auditory evoked potentials. For instance, the auditory late responses (ALRs) and temporal responses (T-complex) show latency and amplitude differences between childhood and adulthood (Bishop et al., 2011; Ponton et al., 2000; Wunderlich et al., 2006). With ALRs, the passage from a biphasic wave (P1 and N2) to a four-peak wave complex (P1, N1, P2 and N2) strongly illustrates the maturation processes of the central auditory system (Ponton et al., 2000; Wunderlich et al., 2006). T-complex responses (Na, Ta and Tb) show a different maturational trend as they have been reported to be present and robust between 5 and 8 years of age. Children have greater response amplitudes (Na, Ta and Tb) than adults (Bruneau et al., 1997; Ponton et al., 2000; Tonnquist-Uhlen et al., 2003). Latencies for

early components (Na and Ta) of T-complex show trends similar to those of fronto-central responses where adults exhibit shorter latencies than children. In contrast, the Tb peak component does not present with a significant latency change into adulthood (Tonnquist-Uhlen et al., 2003), indicating maturational differences between temporal and fronto-central responses.

While the use of ALRs is widespread in investigating auditory processing across lifetime, their relevance is contingent upon the type of listening condition (i.e. quiet vs. noise) in which they are elicited. This limitation arises as wave peak components are barely visible —and thus measurable — in conditions with high disruptive noise, which hinders the visualization and analysis of auditory cortical responses (Benítez-Barrera et al., 2021; Duquette-Laplante et al., 2024). When elicited in noisy conditions, ALRs exhibit notable changes such as amplitude reduction and latency delay, in both children (Anderson et al., 2010; Benítez-Barrera et al., 2022; Gustafson et al., 2019) and adults (Billings et al., 2011; Gustafson et al., 2019; Maamor & Billings, 2017). In addition, the modulation of stimulation parameters can influence wave components. The type of stimuli has an impact as speech stimuli are more resistant to noise than tonal stimuli (Billings et al., 2011). Complex or constant noise have a more detrimental effect than modulated or interrupted noise on wave components (Maamor & Billings, 2017). Signal-to-noise ratio (SNR) had the greatest impact on the waveform components: the higher the SNR, the smaller the effect (Billings et al., 2009; Billings & Grush, 2016; Maamor & Billings, 2017). The impact of stimulus, noise and SNR on ALR results in children and adults were explored (Duquette-Laplante et al., 2024). Of the 12 SNR listening conditions evaluated in noise, only six could be analyzed, thus limiting the findings regarding significant differences between groups. Consequently, ALRs, a traditional electrophysiological measure in audiological research, exhibit limitations in studying central auditory processing in noise. The absence of measurable auditory evoked potentials (AEP) in low SNR noise conditions does not preclude the occurrence of some form of neural auditory processing, which can only be captured using other methods of EEG analysis.

The classical ALRs' approach to studying auditory brain activity averages the time-locked and phase-locked neural responses while disregarding the remainder of the activity in the

electroencephalographic (EEG) signal as noise. However, the post-stimulus EEG signal comprises more than just stimulus-evoked potentials. Other electrophysiological phenomena, such as spontaneous or induced oscillatory neural activity, coexist within the EEG data but cannot be captured by time-locked responses like ALRs (Cohen, 2017; Galambos & Makeig, 1992). This emphasizes the importance of taking a broader perspective on EEG signals to thoroughly investigate the complexity of auditory processing beyond the constraints of time-locked measures. In comparison to ALRs, single trial time-frequency analysis quantifies the power and phase variability of neuronal oscillatory responses across trials according to specific time points and frequency bands: delta (0.1-<4 Hz), theta (4-<8 Hz), alpha (8-13 Hz), beta (14-30 Hz), low gamma (>30-80 Hz), and high gamma (>80 Hz) (Kane et al., 2017). The degree of phase synchronization can be described by inter-trial phase coherence (ITPC), which varies between zero (total phase independence) and one (complete synchronization), whereas the magnitude of the signal or power (total power) is described as the activity's amplitude squared, which generally includes two categories: time-locked (evoked power) and non-time-locked (induced power) components (Buzsáki & Draguhn, 2004; Cohen, 2014; Varela et al., 2001).

Cortical oscillations support sensory and motor processes and various cognitive functions, including speech perception and comprehension (Doelling et al., 2014), learning (Begus & Bonawitz, 2020), cognitive control (Buzzell et al., 2019), memory (Palva et al., 2005), and attention (Lakatos et al., 2008). Low- and high-frequency cortical oscillations in the auditory system are associated with distinct mechanisms of speech perception (Von Stein & Sarnthein, 2000; Yellamsetty & Bidelman, 2018). Low-frequency oscillations have been linked to higher-order processes such as listening effort, auditory memory, and attention (Dimitrijevic et al., 2013; Paus et al., 1997; Sarnthein et al., 1998), while high-frequency oscillations are associated with the automatic encoding of acoustic features, feature binding, figure-ground auditory discrimination, and the quality of speech representations (Yellamsetty & Bidelman, 2018).

In adults, disruptive noise has been shown to reduce phase coherence in the delta, theta, and alpha frequency bands, indicating suboptimal functioning of central auditory information processing (Koerner & Zhang, 2015). In children, maturation-related

differences in cortical auditory oscillatory responses under varying challenging listening conditions have yet to be uncovered. However, other objective methods, such as frequency following response (FFR) and ALRs, demonstrate that auditory processing in children is conspicuously impaired by noise (Almeqbel & McMahon, 2015; Gustafson et al., 2019; White-Schwoch et al., 2015). Alongside cortical maturation processes, differences in the developmental trajectory of frequency bands in neural oscillations are observed during childhood and adolescence. A study on the maturational process of phase-locked activity in response to piano and violin sounds reported a general trend of increased phase-locking in oscillatory activity across different age groups and frequency bands (Shahin et al., 2010). The authors highlighted that the age of maximal increase varies, occurring at a younger age for low-frequency bands (< 25 Hz) and at older age for high-frequency bands (> 25 Hz) (Shahin et al., 2010). Other studies have instead demonstrated a decrease in low-frequency activity and an increase in high-frequency activity from childhood to adulthood (Cho et al., 2015; Dustman et al., 1999; Vanvooren et al., 2015).

1.1. Objectives

The present study aimed to investigate the neural oscillatory activity of children and adults in both quiet and noise conditions. Specifically, the goals were twofold: (1) to examine how cortical oscillatory activity in quiet differ between age groups in regions of interest, and (2) to explore how the modulation of different listening conditions (i.e. type of stimulus, types of noise and SNRs) impact differently children's and adults' cortical oscillatory responses and their scalp distributions. Both ITPC and total power analysis have been used to gain a deeper understanding of auditory processing mechanisms beyond the scope of traditional time-locked responses. Regarding the first goal, we predict that adults and children will have different ITPC and spectral values as these values change with the maturation process of the central auditory system and the brain (Cho et al., 2015; Dustman et al., 1999; Shahin et al., 2010; Vanvooren et al., 2015; Yordanova et al., 2002; Yordanova & Kolev, 2009). For the second goal, variations in types of stimulus, listening conditions, types of noise and SNRs will differentially impact oscillatory activity in children and adults (Fallon et al., 2000; Leibold et al., 2016; Talarico et al., 2007). For both adults and children, verbal stimuli should be more resistant to noise than tonal stimuli (Duquette-Laplante et

al., 2024; Billings et al., 2011), smaller SNRs should have a more disruptive effect on oscillatory activity (Duquette-Laplante et al., 2024; Billings et al., 2011; Maamor & Billings, 2017), and babble noise should be more disruptive than white noise (Duquette-Laplante et al., 2024; Billings et al., 2011; Maamor & Billings, 2017). Such findings hold implications for understanding the impact of environmental noise on auditory processing and may inform strategies for optimizing speech perception abilities in children and adults.

2. Results

2.1. Quiet conditions

Results from the three-way mixed factorial ANOVAs with the factors Stimuli (Tonal, Verbal), Electrode (temporal left, central and temporal right) and Group (Children and Adults) for both frequency bins (theta-alpha – ta and beta-gamma – bg) for the ITPC (phase) and Total Power (power) values are presented in Table 1 and summarized below (see Supplementary materials for detailed ANOVA decompositions). The time-frequency representations (TF) of the ITPC and Total Power values in the quiet conditions are showed in Figure 1. Topographical distributions of oscillatory responses varied between children and adults for both phase and power. As illustrated in Figure 1a, in children, tonal stimuli are associated with large ITPC responses over bilateral temporal electrodes in both ta- and bg- frequency ranges. In contrast, adults show the most robust responses in the bg-frequency range over the right temporal scalp regions. For the verbal stimuli, children's responses were lateralized over the left temporal electrode in the ta- frequency range, while adult's responses were most robust in the bg- frequency range over the central electrode. Figure 1b illustrates that total power responses exhibit similar topographical distributions of oscillatory activity for the tonal stimulus, with children showing more robust responses over both left and right temporal electrodes, while adults' responses were more pronounced at the right electrode. The verbal stimulus shows different activity patterns where activity seem to be most robust over left and right temporal electrodes in children while activity seem robust over the central and left electrodes in adults. These observations were confirmed by statistical analysis (Table 1 and Supplemental materials).

Table 1. Mixed factorial ANOVA results for ITPC and power values in the Theta-Alpha and Beta-Gamma frequency ranges for the quiet conditions.

	ITPC					Power				
	df (between groups)	df (within groups)	F	p≤	η2	df (between groups)	df (within groups)	F	p≤	η2
Theta and Alpha frequency range										
Stimulus (S)	1	28	12.436	**0.001**	0.308	1	28	4.494	**0.034**	0.15
Electrode (E)	1.934	54.144	8.826	**<0.001**	0.24	1.567	43.872	10.168	**<0.001**	0.266
Group (G)	1	28	5.73	**0.024**	0.17	1	28	8.074	**0.008**	0.224
S × G	1	28	3.721	0.064	0.117	1	28	4.791	**0.037**	0.146
E × G	1.934	54.144	12.424	**<0.001**	0.307	1.567	43.872	4.891	**0.011**	0.149
S × E	2	56	1.344	0.269	0.046	2	56	2.540	0.088	0.083
S × E × G	2	56	3.124	0.052	0.1	2	56	0.656	0.523	0.023
Beta and Gamma frequency range										
Stimulus (S)	1	28	3.683	0.065	0.116	1	28	0.076	0.785	0.003
Electrode (E)	1.833	51.314	31.775	**<0.001**	0.532	2	56	1.177	0.316	0.040
Group (G)	1	28	1.468	0.236	0.050	1	28	2.618	0.117	0.085
S × G	1	28	5.926	**0.022**	0.175	1	28	0.638	0.431	0.003
E × G	1.833	51.314	18.285	**<0.001**	0.395	2	56	0.704	0.499	0.025
S × E	1.867	52.276	16.793	**<0.001**	0.375	2	56	0.866	0.426	0.030
S × E × G	1.867	52.276	3.525	**0.036**	0.112	2	56	1.504	0.231	0.051

2.1.1. ITPC

2.1.1.1. Results of the statistical analysis of ITPC measured in the theta and alpha frequency range (ta-ITPC) showed a significant main effect of Group [$F(1,28) = 5.73$, $p = .024$, $\eta^2 = .041$], indicating greater ta-ITPC in children than in adults. The effect of Stimulus [$F(1,28) = 12.436$, $p = .001$, $\eta^2 = .036$] was also significant, showing that the verbal stimulus elicited larger ta-ITPC responses than the tonal stimulus. The significant effect of Electrode [$F(1.93,54.14) = 8.826$, $p < .001$, $\eta^2 = .24$], differed between groups [Group × Electrode interaction: $F(1.93,54.14) = 12.424$, $p < .001$, $\eta^2 = .307$]. Further pairwise comparisons revealed that, in children, stronger ta-ITPC responses were distributed over bilateral temporal scalp regions when compared to central regions [left and right vs. central: $t > 3.023$, $p_{bonferroni} < .005$, $d > .781$; left vs. right: $t = 1.935$, *ns*], no ta-ITPC signal strength difference was observed between electrodes in adults [all pairwise comparisons: $t < 1.369$, *ns*]. All other interactions were non-significant.

2.1.1.2. For the ITPC values of the beta-gamma cortical oscillatory activity (bg-ITPC), the mixed-factorial ANOVA revealed a significant Stimulus × Electrode × Group [$F(1.87,52.28) = 3.525$, $p = .036$, $\eta 2 = .112$] interaction. Pairwise comparisons showed that in adults, bg-ITPC responses did not differ between verbal and tonal stimuli [$t < .486$, *ns*], and their scalp distribution was homogeneous across temporal and central electrodes for both stimulus conditions [$t < 2.155$, *ns*]. In contrast, in children, the tonal stimulus elicited greater bg-ITPC responses than the verbal stimulus over the right temporal electrode only [$t = 4.961$, $p_{bonferroni} < .001$, $d = 1.28$]; no bg-ITPC stimulus differences were found over central and left temporal electrodes [$t < 3.348$, *ns*]. Additionally, in children's results, for both verbal and tonal stimuli, strong ITPC signals were predominantly distributed bilaterally over temporal electrodes with very weak responses recorded over central electrodes [left and right vs. central: $t > 3.237$, $p_{bonferroni} < .007$, $d > .835$; left vs. central: $t < 2.517$, *ns*].

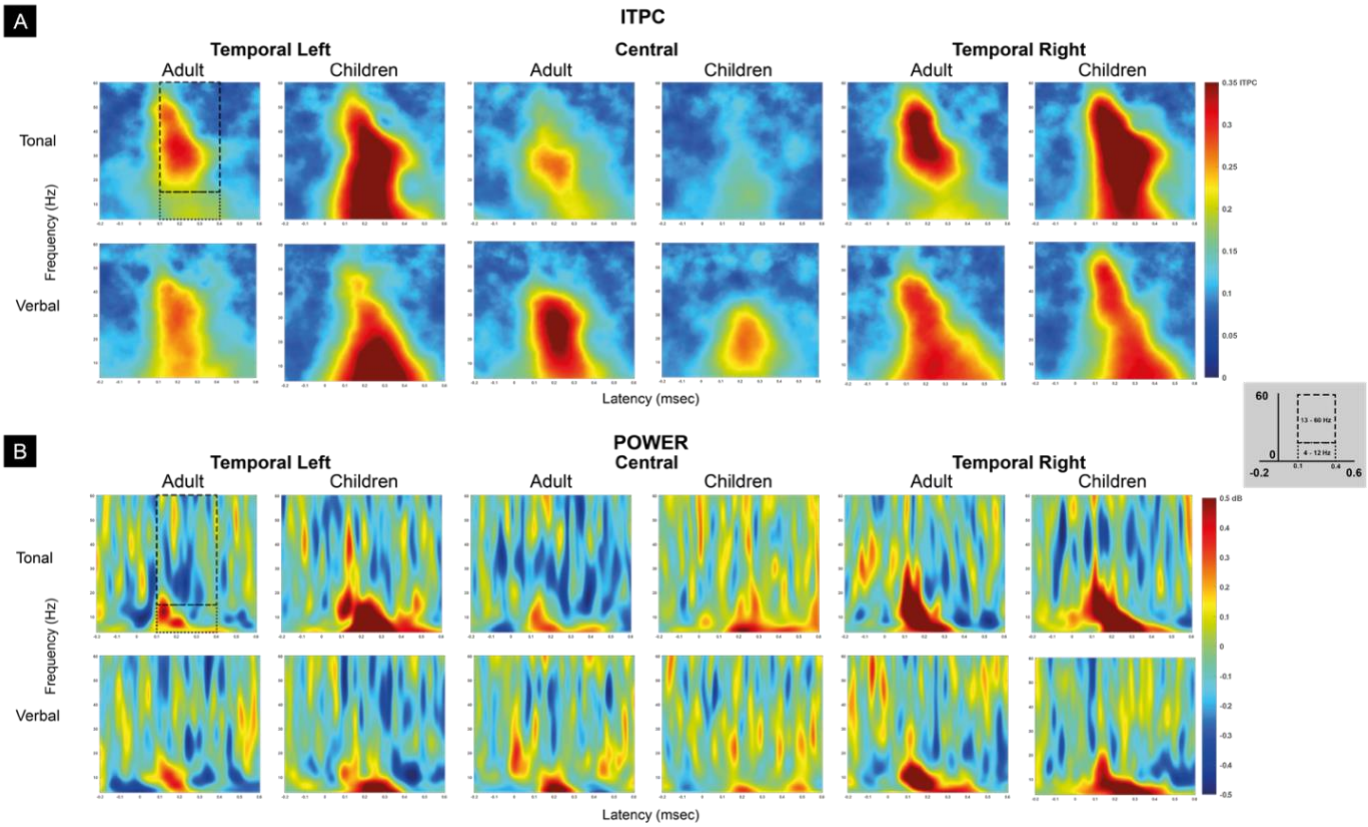

Figure 1. ITPC and total Power quiet conditions time-frequency representations are displayed for the temporal left, central and temporal right electrodes for the verbal and tonal stimuli in children and adults. *Dotted boxes represent time and frequency ranges analysed for the theta-alpha (4-12 Hz) and beta-gamma frequency ranges (13-60 Hz).*

2.1.2. Total power

2.1.2.1. For the Total Power values of the theta-alpha cortical oscillatory activity (ta-Power), the mixed-factorial ANOVA revealed a significant Stimulus × Group interaction [$F(1,28) = 4.791$, $p = .037$, $\eta^2 = .146$] where the tonal stimulus elicited greater power values than the verbal stimulus in children [$t = 2.545$, $p_{bonferroni} = .023$, $d = .657$] but not in adults [$t = 0.035$, *ns*]. There was also a significant Group × Electrode interaction [$F(1.567,43.872) = 4.891$, $p = .011$, $\eta^2 = .149$]. In children, ta-Power was distributed over the temporal electrodes while the central electrode recorded weaker responses [left and right vs. central: $t > 2.951$, $p_{bonferroni} < .011$, $d > .761$; left vs. right: $t = .059$, *ns*]. In contrast, in adults, results showed that ta-Power responses differed at the temporal electrodes where power values were greater at the right than at the left temporal electrode [left vs. right: $t = 4.478$, $p_{bonferroni} < .001$, $d = 1.121$], while the central electrode did not differ from either temporal electrode [central vs. left and right: $t < 2.201$, *ns*].

2.1.2.2. Statistical analysis of Total Power recorded in the beta and gamma frequency range (bg-Power) showed no significant main effects or interactions.

2.2. Noise conditions

The five-way ANOVA results for the ITPC and power analysis of ta- and bg- frequency range responses are presented in Table 2 and summarized below (see Supplementary materials for detailed ANOVA decompositions). Figures 2 to 5 illustrate the effects of noise conditions on ta- and bg- ITPC and Power values, respectively. Overall, the results show that low SNR and Babble noise are associated with reduced ITPC and power values, with a greater impact observed in children than in adults.

Table 2. Mixed factorial ANOVA results for ITPC and power values in the Theta-Alpha and Beta-Gamma frequency ranges for the noise conditions.

	ITPC					Power				
	df (between groups)	df (within groups)	F	p≤	η2	df (between groups)	df (within groups)	F	p≤	η2
Theta and Alpha frequency range										
Stimulus (S)	1	28	1.012	0.323	0.035	1	28	7.161	**0.012**	0.204
Noise (N)	1	28	63.675	**<0.001**	0.695	1	28	11.19	**0.002**	0.298
Electrode (E)	1.997	55.905	4.430	**0.016**	0.137	2	56	2.073	0.135	0.069
Signal to noise ratio (SNR)	1.843	51.61	26.371	**<0.001**	0.485	2	56	2.024	0.142	0.067
Group (G)	1	28	9.862	**0.004**	0.260	1	28	7.169	**0.012**	0.204
SNR × G	2	56	1.081	0.346	0.037	2	56	2.465	0.094	0.081
SNR × S	2	56	2.947	0.061	0.095	2	56	0.466	0.63	0.016
SNR × N	1.771	49.581	6.750	**0.002**	0.194	2	56	0.250	0.78	0.009
SNR × E	3.669	102.741	4.403	**0.002**	0.136	3.652	102.262	2.488	**0.047**	0.082
S × G	1	28	0.022	0.883	0.001	1	28	1.936	0.175	0.065
S × N	1	28	5.230	**0.03**	0.157	1	28	0.124	0.728	0.004
N × G	1	28	3.867	0.059	0.121	1	28	2.849	0.103	0.092
E × G	1.997	55.905	10.425	**<0.001**	0.271	1.65	46.194	6.095	**0.004**	0.179
S × E	1.947	54.506	10.781	**<0.001**	0.278	2	56	2.359	0.104	0.078
N × E	1.861	52.117	14.210	**<0.001**	0.337	1.665	46.607	4.420	0.017	0.136
S × N × G	1	28	0.005	0.945	0.000	1	28	4.922	**0.035**	0.150
N × E × G	1.861	52.117	5.365	**0.007**	0.161	2	56	0.469	0.628	0.016
S × SNR × G	1.975	55.29	5.914	**0.005**	0.174	2	56	1.778	0.178	0.060
SNR × S × E	4	112	0.537	0.709	0.019	4	112	0.672	0.613	0.023
SNR × N × G	1.771	49.581	3.187	**0.049**	0.102	2	56	0.451	0.639	0.016
S × N × SNR	1.969	55.127	15.997	**<0.001**	0.364	2	56	0.150	0.861	0.005
SNR × E × G	4	112	2.004	0.099	0.067	4	112	1.528	0.199	0.052
SNR × N × E	3.566	99.851	6.696	**<0.001**	0.193	4	112	1.373	0.248	0.047
S × N × E	2	3.071	2.111	0.131	0.070	1.484	41.551	0.421	**0.032**	0.116
S × E × G	2	56	0.436	0.649	0.015	2	56	2.507	0.091	0.082
S × SNR × E × G	4	112	2.363	0.057	0.078	4	112	2.202	0.096	0.067
S × N × E × G	2	56	1.390	0.257	0.047	2	56	0.628	0.537	0.022
S × N × SNR × E	3.424	95.874	7.520	**<0.001**	0.212	3.14	87.93	2.775	**0.03**	0.090
S × N × SNR × G	2	56	2.773	0.071	0.090	2	56	2.022	0.142	0.067
N × SNR × E × G	3.566	99.851	4.090	**0.004**	0.127	4	112	1.416	0.233	0.048
S × N × SNR × E × G	3.424	95.874	6.386	**<0.001**	0.186	4	112	0.459	0.766	0.016
Beta and Gamma frequency range										
Stimulus (S)	1	28	42.533	**<0.001**	0.603	1	28	0.231	0.634	0.008
Electrode (E)	1.943	54.41	7.663	**0.001**	0.215	2	56	0.963	0.388	0.033
Noise (N)	1	28	198.695	**<0.001**	0.876	1	28	1.121	0.299	0.039
Signal to noise ratio (SNR)	1.859	52.064	30.626	**<0.001**	0.522	2	56	1.522	0.277	0.052
Group (G)	1	28	2.501	0.125	0.082	1	28	4.891	**0.035**	0.149
SNR × G	2	56	0.643	0.529	0.022	2	56	3.415	**0.04**	0.109
SNR × S	2	56	0.165	0.848	0.006	1.694	47.434	3.575	**0.035**	0.113
SNR × E	3.47	97.155	8.759	**<0.001**	0.238	4	112	1.236	0.3	0.042
SNR × N	1.711	47.895	10.421	**<0.001**	0.271	2	56	2.367	0.103	0.078
S × G	1	28	7.67	**0.01**	0.215	1	28	1.136	2.960	0.008
S × N	1	28	2.13	0.156	0.071	1	28	0.450	0.508	0.016

N × G	1	28	2.081	0.16	0.069	1	28	0.075	0.786	0.003
E × G	1.943	54.41	23.477	**<0.001**	0.456	2	56	0.637	0.533	0.022
S × E	1.903	53.286	49.064	**<0.001**	0.637	2	56	0.282	0.756	0.010
N × E	1.974	55.28	29.903	**<0.001**	0.516	2	56	0.721	0.491	0.025
S × N × G	1	28	2.44	0.129	0.08	1	28	0.388	0.539	0.014
N × E × G	1.974	55.28	7.471	**0.001**	0.211	2	56	0.946	0.394	0.033
S × SNR × G	2	56	2.305	0.109	0.076	1.694	47.434	3.734	**0.03**	0.118
SNR × S × E	4	112	2.125	0.082	0.071	4	112	0.868	0.485	0.030
SNR × N × G	2	56	0.847	0.434	0.029	2	56	0.303	0.74	0.011
S × N × SNR	1.934	54.161	31.868	**<0.001**	0.532	2	56	0.297	0.744	0.010
SNR × E × G	4	112	2.379	0.056	0.078	4	112	0.299	0.878	0.011
SNR × N × E	3.114	87.196	24.507	**<0.001**	0.467	4	112	1.788	0.136	0.060
S × N × E	1.781	49.861	3.996	**0.029**	0.125	2	56	0.597	0.554	0.021
S × E × G	1.903	53.286	5.475	**0.008**	0.164	2	56	1.497	0.233	0.051
S × SNR × E × G	4	112	0.254	0.906	0.009	4	112	0.547	0.702	0.019
S × N × E × G	2	56	0.055	0.946	0.002	1.933	54.13	5.844	**0.005**	0.173
S × N × SNR × E	2.716	76.041	41.289	**<0.001**	0.596	4	112	1.345	0.258	0.046
S × N × SNR × G	2	56	2.842	0.067	0.092	2	56	0.833	0.44	0.029
N × SNR × E × G	3.114	87.196	2.474	0.065	0.081	4	112	0.840	0.503	0.029

2.2.1. ITPC

2.2.1.1. The statistical results of the measured ta-ITPC revealed a significant Electrode × Stimulus × Noise × SNR × Group interaction [$F(3.42,95.87) = 6.386$, $p < .001$, $\eta^2 = .186$]. To better understand this five-way interaction, we conducted further statistical analysis separately over each electrode.

For the left temporal electrode, the Stimulus × Noise × SNR × Group interaction was significant [$F(2,56) = 4.54$, $p = .015$, $\eta^2 = .14$]. This interaction indicates that ta-ITPC values were more reduced in children than adults when elicited by the tonal stimulus embedded in the babble noise, irrespective of the SNR level [$t > 3.542$, $p_{bonferroni} < .001$, $d > 1.293$]. In contrast, when the tonal stimulus was embedded in a white noise, age-related decreases in ta-ITPC were significant only at the lowest SNR level [0 : $t = 3.693$, $p_{bonferroni} < .001$, $d = 1.348$; +10 and +5: $t < 2.082$, *ns*]. For the verbal stimulus, only the babble noise resulted in a greater reduction of ta-ITPC values in children than in adults [babble: $t = 3.036$, $p_{bonferroni} = .005$, $d = 1.109$; white: $t = 2.017$, *ns*]. The main effect of the SNR factor was also significant and only the greatest SNR (+10 dB SNR) elicited smaller reduction than both the smallest SNRs [+10 vs. +5 and 0 : $t > 2.844$, $p_{bonferroni} < .009$, $d > .518$; +5 and 0: $t = 1.817$, *ns*]

For the central electrode, the tonal stimulus reduced the ta-ITPC values less than the verbal stimulus [$F(1,28) = 2.579$, $p < .001$, $\eta^2 = .424$]. The Noise factor indicated that babble noise reduced ta-ITPC values less than the white noise [$F(1,28) = 14.623$, $p < .001$, $\eta^2 = .343$]. Furthermore, the smallest SNR (0 dB) yielded the largest reductions in ta-ITPC values [0 vs. +5 and +10: $t > 2.549$ $p_{bonferroni} < .017$ $d > .465$; +5 vs. +10: $t < .496$, *ns*].

For the right temporal electrode, there was a significant interaction of Stimulus × Noise × SNR × Group [$F(2,56) = 7.268$, $p = .002$, $\eta^2 = .206$]. Further analysis of the Noise × SNR × Group interaction was conducted by isolating the Stimulus factor. For the tonal stimulus, only the main effect of the Noise factor where ta-ITPC responses were significantly reduced in the presence of white noise as compared to the presence of babble noise [$F(1,28) = 19.385$, $p < 0.001$, $\eta^2 = .409$] and the main effect of the SNR factor where the smallest SNR yielded significantly smaller values than both higher SNR conditions [+10 and +5 vs. 0: $t > 2.777$, $p_{bonferroni} < .01$, $d > .506$; +10 vs +5: $t = .702$, *ns*] were significant. For the verbal stimulus, white noise decreased ta-ITPC values in to a greater extent in adults than in children [$F(1,28) = 11.477$, $p = 0.002$, $\eta^2 = .291$]. Moreover, when the verbal stimulus was embedded in a babble noise, when compared to adults, children showed stronger ta-ITPC responses at both the +10 and the +5 dB SNR levels [$t > 2.594$, $p_{bonferroni} < .017$, $d > .946$; 0] but not at the 0 dB SNR [$t = .210$, *ns*].

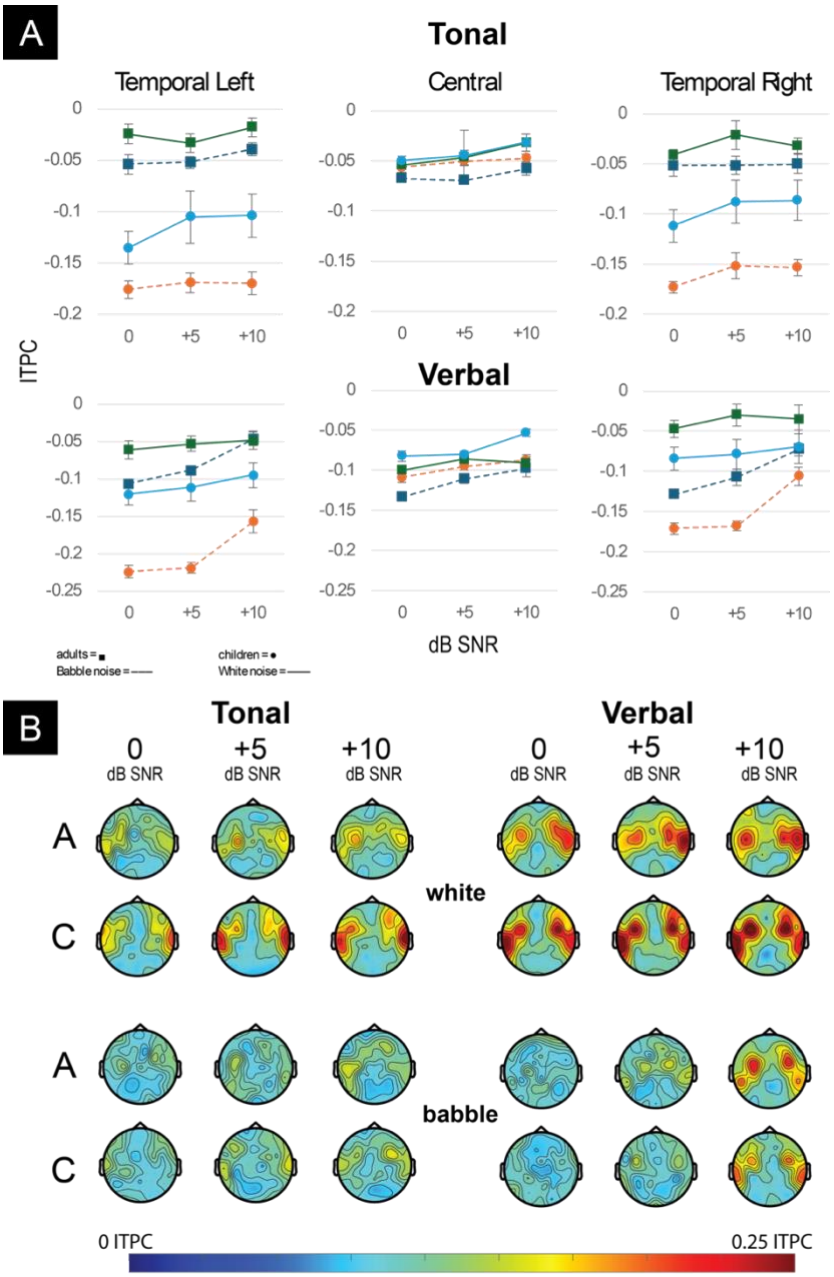

Figure 2. A) ta-ITPC mean values (standard errors) for all noise listening conditions for the verbal and tonal stimulus in children and adults B) ta-ITPC topoplots for all noise conditions for the verbal and tonal stimulus in children (C) and adults (A).

2.2.1.2. For the ITPC values of the beta-gamma cortical oscillatory activity (bg-ITPC), results revealed no differences between groups [Group: $F(1,28) = 2.501$, $p = .125$, $\eta^2 = .082$] and no significant interactions that included the group factor. However, there was a significant Stimulus × Noise × SNR × Electrode interaction [$F(2.716,76.041) = 41.289$ p

< .001, η^2 = .596]. Further analyses of this interaction were conducted by isolating the Electrode factor.

In the left electrode, results revealed that the white noise conditions elicited larger bg-ITPC values than babble noise [F(2.716,76.041) = 41.289, p < .001, η^2 = .596]. Moreover, only the most favourable SNR yielded greater bg-ITPC values than the smallest SNR, while the +5 dB sNR condition was not significantly different from either the +10 or the 0 dB SNR conditions [+10 vs. 0: t > 3.927, $p_{bonferroni}$ < .001, d > .716; +10 and 0 vs. +5: t < 2.084, *ns*].

In the central electrode, with the significant Stimulus × Noise × SNR interaction [F(2,58) = 3.692, p = .031, η^2 = .240], further analyzes of the interaction Noise × SNR was conducted when the Stimulus factor was isolated. For the tonal stimulus, the white noise condition elicited larger bg-ITPC responses than the babble noise condition [F(1,28) = 12.436, p = .001, η^2 = .036]. For the verbal stimulus, babble noise elicited similar bg-ITPC values between SNR conditions [t < .672, *ns*], while in the white noise, only the greatest SNR elicited greater bg-ITPC values than the smallest SNR [+10 vs +5 and 0: t > 3.850, $p_{bonferroni}$ < .0041 d > .702; +5 vs 0: t = 1.325, *ns*].

In the right electrode, Stimulus × Noise × SNR interaction was significant [F(2,58) = 3.692, p = .031, η^2 = .113]. Further analyses of the interaction Noise × SNR was conducted by isolating the Stimulus factor. For the tonal stimulus, in the babble noise condition, only the 0 dB SNR condition elicited smaller bg-ITPC values than the +5 dB SNR [+5 vs 0: t = 2.591, $p_{bonferroni}$ = .015, d = .473; +10 vs +5 and 0: t < 2.015, *ns*]. In contrast, with the tonal stimulus in white noise, the bg-ITPC responses were significantly smaller for each SNR condition [+10 > +5 > 0: t > 3.003, $p_{bonferroni}$ < .006, d > .547]. For the verbal stimulus in the babble noise condition, the SNR effect was systematic, the smaller the SNR, the smaller the bg-ITPC values [+10 > +5 > 0: t > 2.79, $p_{bonferroni}$ < .01, d > .509], while in the white noise, only the 0 dB SNR condition reduced the bg-ITPC values more than the other SNR conditions [0 vs +5 and +10: t > 3.405, $p_{bonferroni}$ < .003, d > .621; +5 vs +10: t = .232, *ns*].

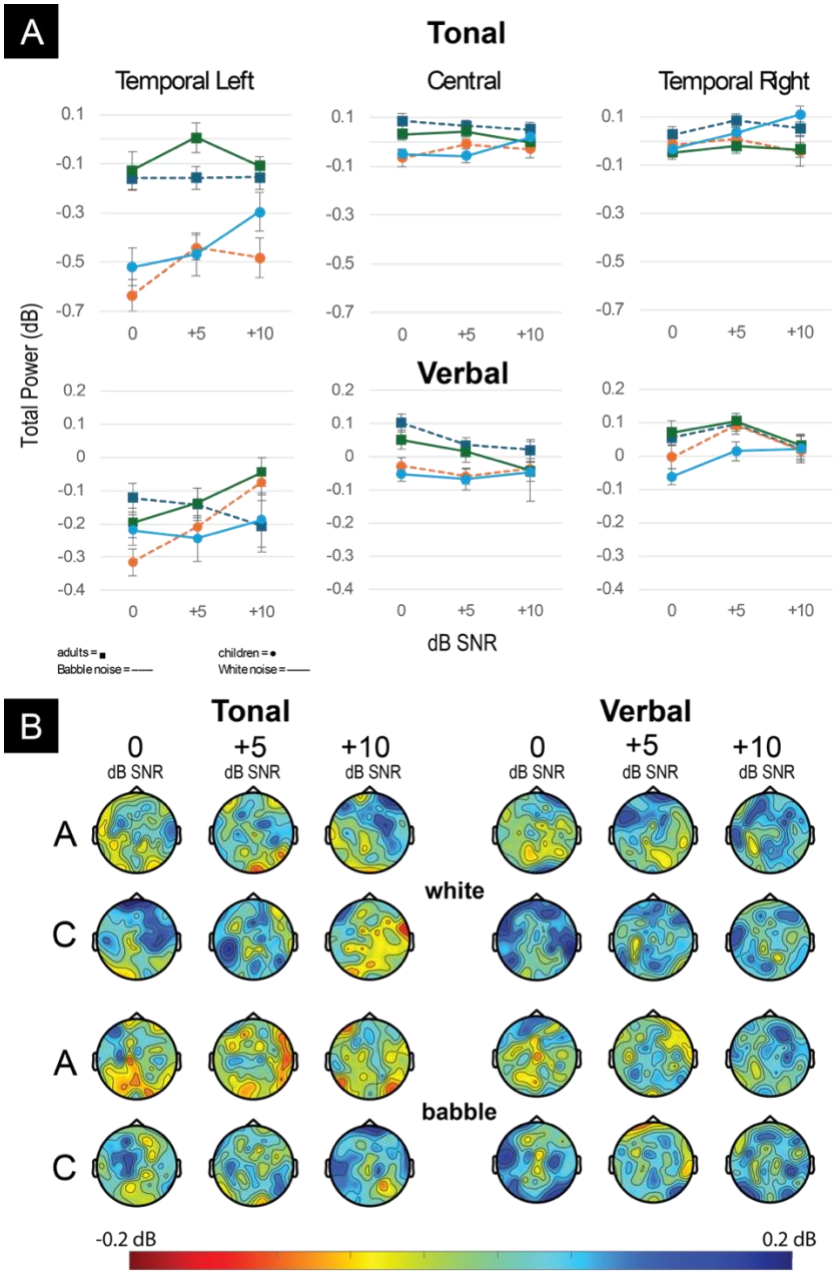

Figure 3. A) bg-ITPC mean values (standard errors) for all noise listening conditions for the verbal and tonal stimulus in children and adults B) bg-ITPC topoplots for all noise conditions for the verbal and tonal stimulus in children (C) and adults (A).

2.2.2. Total power

2.2.2.1. In the theta and alpha frequency range, the statistical analysis of the measured ta-Power showed a significant interaction of Stimulus × Noise × SNR × Electrode

[$F(3.14,87.93) = 2.775$, $p = .03$, $\eta^2 = .09$]. The interaction Stimulus × Noise × SNR with the isolation of the Electrode factor was further analyzed. In both the left and the central electrode, no main effects or interactions were significant [$F < 2.92$, *ns*]. For the right electrode, the tonal stimulus elicited smaller bg-Power values than the verbal stimulus [$F(1,29) = 11.883$, $p = .002$, $\eta^2 = .291$]. The babble noise also produce greater reductions of the ta-Power values than the white noise [$F(1,29) = 16.044$, $p < .001$, $\eta^2 = .356$]. Furthermore, the 0 dB SNR elicited smaller ta-Power responses than the two other SNR conditions [+10 and +5 vs. 0: $t > 3.508$, $p_{bonferroni} < .004$, $d > .905$; +10 vs. +5: $t = .003$, *ns*].

Moreover, for the ta-Power, the Stimulus × Noise × Group [$F(1,28) = 4.922$, $p = .035$, $\eta^2 = .150$] interaction was also significant. The Stimulus factor was isolated and analysis of the Noise × Group interaction was conducted. For the tonal stimulus in the babble noise, ta-Power values in children were significantly more reduced than in adults, but not in the white noise condition [$t = 3.008$, $p_{bonferroni} = .006$, $d = 1.098$; $t = 1.619$, *ns*]. For the verbal stimulus, the babble noise condition had a more detrimental impact on the ta-Power values than the white noise [$F(1,28) = 4.63$, $p = .04$, $\eta^2 = .142$].

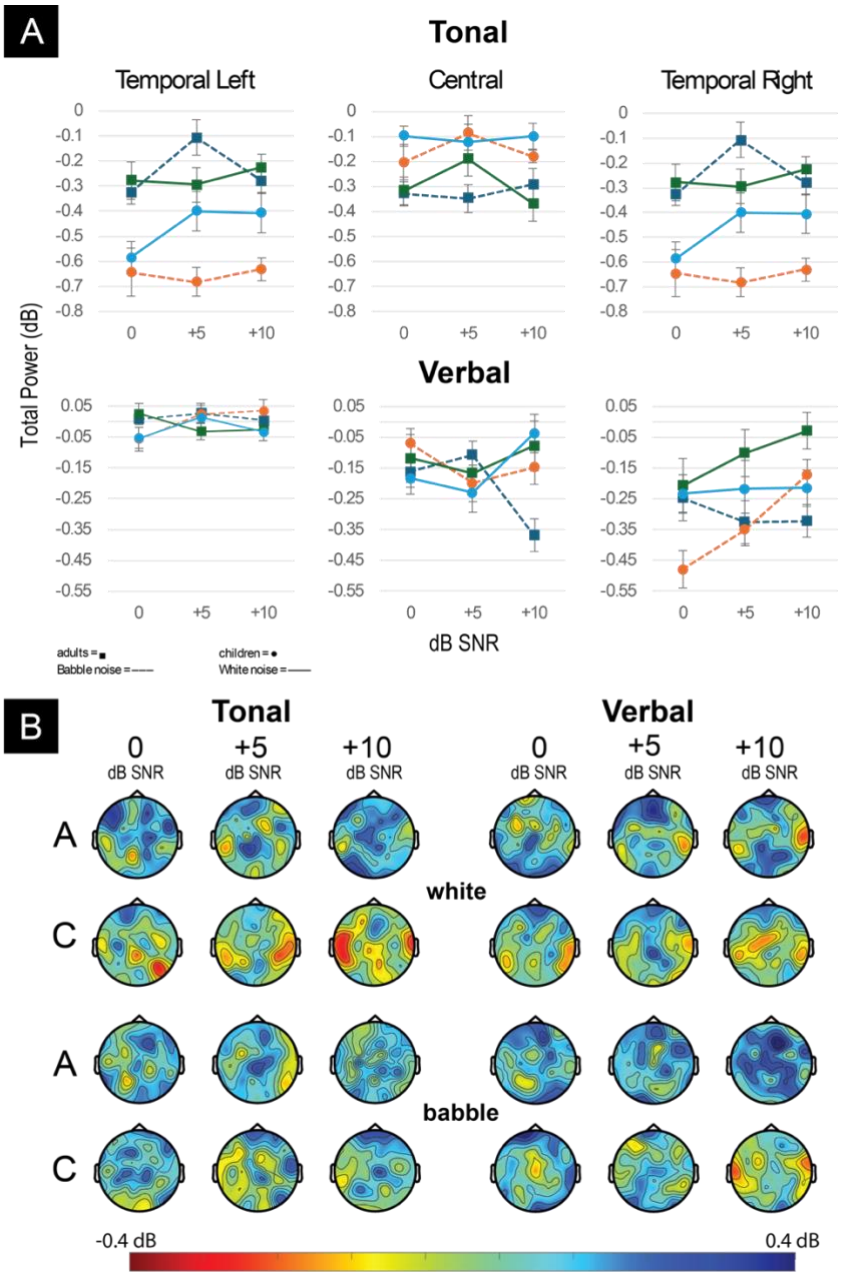

Figure 4. A) ta-Power mean values (standard errors) for all noise listening conditions for the verbal and tonal stimulus in children and adults B) ta-Power topoplots for all noise conditions for the verbal and tonal stimulus in children (C) and adults (A).

2.2.2.2. For the Power values of the beta-gamma cortical oscillatory activity (bg-Power), the Electrode x Stimulus × Noise × Group interaction [$F(1.933,54.13) = 5.844$, $p = 0.005$, $\eta^2 = .173$] was significant. The Electrode factor was isolated and the interaction Stimulus × Noise × Group was analyzed. For the left electrode, no main effects of stimulus, noise and group or interactions were significant [$t < 2.974$, *ns*]. For the central electrode, only the main effect of the Group factor was significant where adults had smaller bg-Power reductions than children [$F(1,28) = 6.403$, $p = .017$, $\eta^2 = .186$]. For the right electrode, there were no significant differences between stimuli, groups or noise conditions and no significant interactions [$F < 1.393$, ns; $t < 1.230$, *ns*].

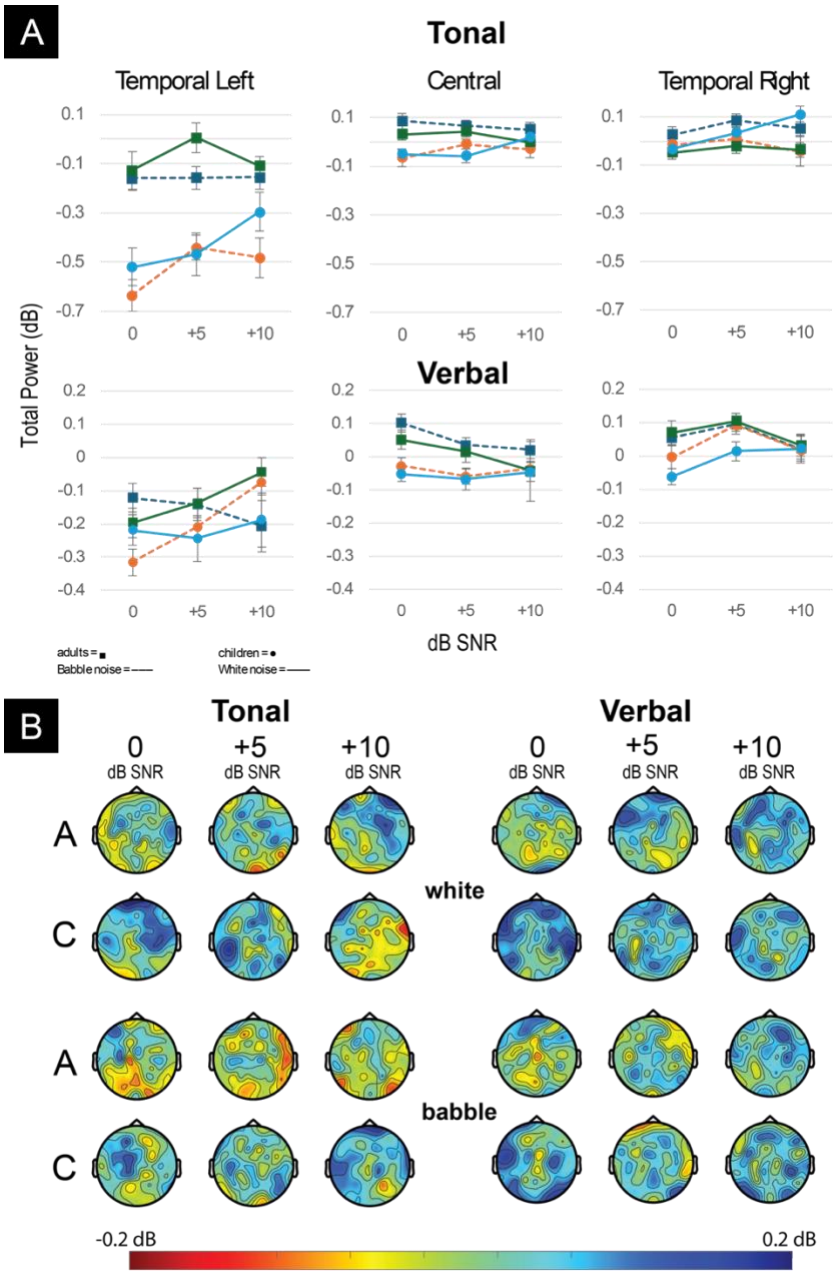

Figure 5. A) bg-Power mean values (standard errors) for all noise listening conditions for the verbal and tonal stimulus in children and adults B) bg-Power topoplots for all noise conditions for the verbal and tonal stimulus in children (C) and adults (A).

3. Discussion

The current study explored, in children and adults, the impact of various auditory stimuli, types of noise and SNR levels on the pattern of cortical oscillatory activity in children and adults. We employed ITPC and total power analyses to investigate the mechanisms

underlying auditory processing under these different listening conditions. The modulation of the different recording parameters revealed that phase synchronization across trials and spectral power values were most significant for children and adults in quiet. At the same time, lower SNRs, babble noise, and tonal stimuli were associated with smaller phase synchronization and power values.

3.1.Topographical group differences

Current findings revealed different power and ITPC patterns between groups depending on electrode positions. Adults had higher ITPC and total power values than children in the fronto-central scalp region for theta-alpha and beta-gamma frequency ranges. However, children's ITPC and power values were greater than adults' over temporal electrodes. These marked differences in power and ITPC support previous findings regarding the independence of temporal and fronto-central auditory generators and their distinct maturational time courses (Bishop et al., 2011; Ponton et al., 2000). Fronto-central auditory processing generators attain maturity later than temporal generators (Bishop et al., 2011; Cho et al., 2015; Müller et al., 2009; Ponton et al., 2000). The differences between children and adults in the central electrode position with the increase in phase synchronization and a decrease in power in the left temporal electrode underline transitional patterns in oscillatory activity across the lifespan, from childhood to adulthood (Cho et al., 2015; Müller et al., 2009; Vanvooren et al., 2015; Yordanova & Kolev, 2009). Bishop and collaborators (2011) observed similar results: increased phase-locking values in their fronto-central electrode and reduced trend in their temporal electrode in children ?. High levels of theta-alpha frequency range oscillatory activity in the temporal electrodes could be considered as a neuromarker of an immature auditory system when processing auditory stimulation (Dimitrijevic et al., 2013; Paus et al., 1997; Sarnthein et al., 1998; Tonnquist-Uhlen et al., 2003). These oscillations are usually associated with cognitively related activities such as listening effort and auditory memory (Dimitrijevic et al., 2013; Paus et al., 1997; Sarnthein et al., 1998; Tonnquist-Uhlen et al., 2003). On the other hand, the increase in beta-gamma frequency range oscillatory activity could be related to more efficient sensory processing seen in adults, as the extraction of global phonetic features, automatic encoding of acoustic features and template matching are all driven by beta-

gamma frequency range activity (Bidelman, 2015, 2017; Bidelman & Yellamsetty, 2017; Von Stein & Sarnthein, 2000; Yellamsetty & Bidelman, 2018).

3.2. Stimulus type

Cortical synchronization patterns were observed in response to tonal and verbal stimuli. Both children and adults showed greater ITPC values over all electrodes for the verbal stimulus than the tonal stimulus, as phase synchronization information is greater for more complex sounds when compared to more simple sounds (Shahin et al., 2010). Adults had smaller ITPC values for the tonal stimulus than for the verbal stimulus, indicating greater efficiency of their auditory system in processing simple rather than complex sounds (Yordanova et al., 2002). ERP literature also supports these results, as different linguistic and non-linguistic stimuli processing mechanisms exist (Bishop et al., 2011; Ceponiene et al., 2005; Koravand, 2013; Koravand et al., 2012).

3.3. Type of noise type and SNR

Noise and SNR impacted both power and ITPC, leading to a reduction in overall oscillatory activity. Children were more affected by noise than adults in both power and phase synchronization, consistent with behavioral literature (Hall, 1992; Leibold et al., 2016). Two noise parameters were modulated: the type of noise (Babble noise versus White noise) and the SNR (0, +5, +10 dB). The impact of these parameters, particularly on phase synchronization values, provided greater insight into the effect of the noise modulation in children and adults. Overall, the combination of white noise and SNR seemed to have a more systematic impact on both ITPC and power values, as generally, smaller SNRs induced greater reductions.

Such results align with previous reports using ALR measures, where SNR is recognized as one of the most influential response modulators (Benítez-Barrera et al., 2021; Billings et al., 2009; Duquette-Laplante et al., 2024; Maamor & Billings, 2017; Papesh et al., 2015). However, the combination of babble noise and SNR did not consistently show such systematic effects. In some instances, both children and adults exhibited unmeasurable data because the stimuli were undetectable among the noise, especially with the lowest SNR.

The babble noise was found to be more detrimental to ITPC and power in response to tonal and verbal stimuli (Maamor & Billings, 2017) compared to white noise. This contrasts with previous studies that indicated no differences between evoked responses in noise in adults and children (Gustafson et al., 2019) or adults had systematically greater ITPC values than children (Müller et al., 2009). The current results demonstrate that noise has a greater impact on children in certain conditions and that children exhibit greater ITPC values than adults over the temporal electrodes. In noisy conditions, these differences diminished indicating a greater reduction of both ITPC and phase values in children. Children experienced a more substantial reduction of ITPC values when tested in noise compared to quiet conditions. In contrast, adults had overall lower ITPC values than children, their auditory cortical responses appeared more resilient in adverse listening conditions. These findings are compatible with behavioral studies reporting that children do not perform as well as adults in noisy environments (Buss et al., 2018; Hall et al., 2002; Leibold et al., 2016).

4. Limitations

As behavioral measures in noise were not conducted in the current study, there are limitations in translating oscillatory patterns into behavioral differences for children and adults. Future studies should include such measures to provide further insights into the potential associations. The sample size for each group in the current study was small and, combined with the large number of conditions, could have hindered the statistical power of the differences between groups. ITPC and power values varied, especially in children. The cross-sectional design limited the ability to understand and infer relationships between cortical oscillations, stimulus characteristics, and the maturation of auditory processing mechanisms, as only two age groups were included. A larger sample size with more age groups and a longitudinal design are needed to elucidate these relationships further. Finally, sex was also one of the study's limitations since the children's group had fewer girls than the adult group, which was dominated by women. Given that men and women's hearing systems work slightly differently, this discrepancy could have affected the findings (Morlet et al., 1995; Roche et al., 1978; Tobias, 1965).

5. Conclusion

The current study underlines significant differences between children's and adults' phase synchronization and total power values in quiet and noise. The combination of the type of stimulus, listening conditions, type of noise, and SNR significantly impacted results. These results support previous studies indicating different maturational courses for temporal and frontocentral generators (Bishop et al., 2011; Ponton et al., 2000; Tonnquist-Uhlen et al., 2003). The verbal stimulus was more noise-resistant than the tonal stimulus in most of the testing conditions. Even if strongly affected by noise, results were still analyzable in all conditions compared to time-locked responses, which were mainly absent in the most challenging listening conditions (Duquette-Laplante et al., 2024). As these values are present and robust, they could help further investigate auditory processing under challenging listening situations, especially in populations that are difficult to test behaviorally to have a complete overview of their speech perception in noise. This could support the elaboration of interventions targeting cortical oscillatory activity in the context of auditory processing mechanisms that may mitigate the adverse effects of environmental noise on speech perception.

6. Experimental Procedure

The subject population and data collection methods were outlined by Duquette-Laplante et al. (2024); they will be thoroughly reviewed in the following section. The analyses presented in this study utilize AEP data that were previously discussed by Duquette-Laplante et al. (2024). This study received approval from the ethics committee of the Centre Hospitalier Universitaire (CHU) Sainte-Justine and the University of Ottawa. All subjects or legal guardians of underage participants provided written informed consent before enrollment in the study. Children provided their written assent to participate in the current study.

6.1. Participants

Fifteen young adults (mean ± SD: 24.5 ± 1.6 years, three men) and 15 children aged 8 to 12 (mean ± SD: 9.9 ± 1.4 years, 11 boys) participated in the study. All participants had

normal peripheral hearing with air conduction thresholds of ≤ 15 dB HL for frequencies 0.25 to 8 kHz with normal middle ear function and spoke French as their dominant language. Exclusion criteria for both groups included any history of head injury, chronic otitis, ear surgery, or use of ototoxic medication. Additionally, individuals with medical disorders that could affect the central nervous system – such as congenital, neurological, neurodevelopmental, or metabolic disorders – a diagnosis of intellectual disability or premature birth (<37 weeks) were excluded.

6.2.Stimuli and Procedures

6.2.1. Stimuli

Two types of stimuli were created: a pure tone 1000 Hz stimulus and a speech syllable /da/ with the Pratt software (Boersma & Weenink, 1992), calibrated at a loudness level of 70 dBA (Larson Davis Laboratories Sonometer model 800B). The duration of both stimuli was 170 msec with a rise and a fall time of 10 msec. Two types of noise were also utilized: i) a white noise generated with the Audacity® software (Audacity Team, 1999) and ii) a Canadian eight-talker French babble noise (Lagacé, 2014). The noises were calibrated at three loudness levels, 60, 65 and 70 dBA (Larson Davis Laboratories Sonometer model 800B), resulting in three levels of signal-to-noise ratios: +10 dB SNR, +5 dB SNR and 0 dB SNR. The combination of two types of stimuli, two types of noises and three SNRs (2X2X3) resulted in twelve distinct noise conditions. In addition, the stimuli were also presented without noise (quiet conditions), resulting in a total of fourteen conditions. For each of these fourteen listening conditions, a block of 200 presentations was created with an interstimulus interval jitter between 1130 and 1330 milliseconds (msec). In twelve conditions, the noise was presented continuously for the duration of the block. Each block lasted approximately 4 minutes to 4 minutes 15 seconds.

6.2.2. EEG Data Acquisition

For each participant, the fourteen listening conditions were presented in a pseudorandomized sequence via binaural E-A-RTONE 3A insert earphones connected to an audiometer (MADSEN Midimate 622) and a computer with the software Presentation®

(Neurobehavioral Systems Inc.). A total of 2800 trials, 400 in quiet and 2400 in noise, were presented to each participant. PyCorder software and the Brain Vision actiCHamp™ amplifier with a 64-channel active Ag/AgCl scalp electrode cap (64 electrode actiCAP; Brain Vision LLC) were used to record the continuous EEG dataset. Data were sampled at a rate of 1000 Hz, with the maximum impedance for each electrode limited to 40 kΩ (Mathewson et al., 2017). The analysis window (epoch) was set from -200 to 800 msec. Vertical eye movements were recorded using electrodes positioned below the eyes. The Oz electrode served as the online reference point for EEG recordings. Participants were instructed to ignore the auditory stimuli while lying still in a zero-gravity chair, moving as little as possible, and listening to a muted movie with subtitles.

6.2.3. Pre-processing of EEG Data for Time-Frequency Analysis

EEG data were analyzed in MATLAB (The MathWorks Inc., 2022) using the open-source software toolbox FieldTrip (Oostenveld et al., 2011). Raw data were segmented into epochs ranging from -500 to 1000 msec. Single EEG epochs exceeding ± 100 μV were systematically excluded from subsequent analyses to reduce the influence of muscle artifacts. The Independent Component Analysis (ICA) method was then used to detect and remove eye movement artifacts from the residual EEG signal, including blinks and horizontal movements (Herault & Jutten, 1986; Makeig et al., 1996). The remaining trials were examined individually, and those containing stimulation artifacts were manually excluded. To ensure a representative sample, 100 individual trials per participant were randomly selected from the artifact-free data set for time-frequency analyses. Ultimately, raw EEG segments were transformed into current source density values ($\mu V/cm^2$ units) using a spherical spline surface Laplacian method described by Perrin et al. (1989). The application of the surface Laplacian aimed to accentuate local changes in neural activity while mitigating the influence of distant sources, thereby refining the spatial specificity of the EEG signal.

6.2.4. Time-Frequency Analysis

Time-frequency analyses were performed using the convolution of the EEG signal and a set of complex Morlet wavelets, defined as complex sinusoidal waves filtered by a

Gaussian function. The wavelet frequencies ranged from 2 Hz to 100 Hz with a 0.5 Hz interval. Window widths varied between 2 and 15 cycles.

6.2.4.1. ITPC

The timing and consistency of the timing of phase values over EEG trials were then analyzed using the intertrial phase clustering measure:

$$\mathrm{ITPC_{tf}} = \left| n^{-1} \sum_{r=1}^{n} e^{ik_{tfr}} \right|$$

Where e^{ik} provides the complex polar representation of a phase angle k for trial r at a specific time-frequency point tf (Cohen, 2014), the ITPC value ranges from 0 to 1, representing the absence of synchronization and perfect synchronization of the signal phase between trials, respectively.

6.2.4.2. Total Power

The magnitude of the spectral power in the EEG was calculated and converted to decibels:

$$dB_{tf} = 10\log10\left(\frac{activity_{tf}}{\overline{baseline_{tf}}}\right)$$

Where *t* represents time points, *f* represents frequency points, and the bar above the baseline indicates the mean across a baseline period (-300 to -100 msec) (Cohen, 2014).

6.3. Statistical analysis

Three electrodes of interest were identified based on previous studies (Bishop et al., 2011; Tonnquist-Uhlen et al., 2003): T7, Cz and T8. Four frequency bands (4 to 60 Hz), relating to four of the five canonic frequency bands, theta, alpha, beta and low gamma, were selected as they were involved in auditory processing (Bishop et al., 2011; Koerner & Zhang, 2015; Shahin et al., 2010; Vanvooren et al., 2015; Yellamsetty & Bidelman, 2018; Yordanova & Kolev, 2009). The delta band could not be analyzed due to the small ISI and epoch. A time window of 300 msec from 100 to 400 msec post stimuli was selected as

evoked responses in quiet, and noise were previously established (Bishop et al., 2011; Gustafson et al., 2019; Shahin et al., 2010). The objective was to uncover patterns or trends without rigidly predefined hypotheses since consistent frequency-band-specific time-frequency analysis methods are scarcely available, especially in children, for auditory processing in noise. For this reason, allowing flexibility in the analysis becomes particularly valuable. While some could state that emphasizing the ITPC or power values around specific peaks has increased significance, the current study highlighted broader frequency ranges of the overall ITPC and power derived from a larger window. Therefore, this approach was preferred for comparisons across listening conditions and age groups in an exploratory framework, promoting open and discovery-based data exploration.

For the statistical analysis, total power and ITPC values were extracted from each of the three electrodes (T7, Cz and T8) and averaged across all time points of the selected time window (100-400 msec) and frequencies in two separated two frequency bins: Theta-Alpha (ta-) frequency range: theta (4-7 Hz) and alpha (8-12 Hz) and Beta-Gamma (bg-) frequency range: beta (13-30 Hz) and low gamma (31-60 Hz). Statistical analyses were conducted with IBM SPSS Statistics (Version 29). In order to extract the most information from the noise conditions, analyses were separated into two types: Quiet conditions and Noise conditions. For the quiet conditions, four mixed factorial ANOVAs, two for each frequency category (ta- and bg-), were carried out separately for phase and power values. Each three-way mixed-factorial ANOVA (2×2×3) included Group (children, adults) as a between-subjects factor and Electrode (temporal left – T7, central – Cz and temporal right – T8) and Stimulus (tonal, verbal) as within-subjects factors. For the analysis of both phase and total power values in the noise conditions, the related quiet condition value was subtracted from each of the twelve noise condition values to compare only noise conditions. Four mixed-factorial ANOVAs were carried out separately for each frequency category (ta- and bg-) for the resulting phase and power values. The five-way mixed-factorial ANOVAs (2×2×2×3×3) had four within-subjects factors: Stimulus (tonal, verbal), Noise (white, babble), SNR (+10 dB, +5 dB and 0 dB), Electrode (temporal left – T7, central – Cz and temporal right – T8), and one between-subjects factor, Group (children, adults). The Greenhouse-Geisser corrections were applied when the sphericity of the variance was

violated. The significance level was established at $p<0.05$. In post hoc multiple comparisons, Bonferroni correction was applied ($p < 0.05/k$, where k is the number of comparisons), and Levene's test was applied when necessary if the equal variance assumption was not met.

7. Authors contributions

Fauve Duquette-Laplante: Conceptualization (equal); Data curation (lead); Formal Analysis (equal); Funding Acquisition (equal); Investigation (lead); Methodology (equal); Project administration (lead); Software (equal); Supervision (lead); Validation (lead); Visualization (lead); Writing - Original Draft Preparation (equal); Writing – review and editing (equal). **Aurélie Belleau-Matte:** Formal Analysis (equal); Data curation (supporting); Investigation (supporting); Software (supporting); Supervision (supporting); Visualization (supporting); Writing - Original Draft Preparation (equal); Writing – review and editing (equal). **Boutheina Jemel:** Data curation (supporting); Formal Analysis (equal); Methodology (equal); Software (equal); Validation (supporting); Visualization (supporting); Writing - Original Draft Preparation (equal); Writing – review and editing (equal). **Benoît Jutras:** Conceptualization (equal); Formal Analysis (supporting); Funding Acquisition (equal); Methodology (equal); Project Administration (supporting); Resources (equal); Supervision (lead); Validation (lead); Writing - Original Draft Preparation (equal); Writing – review and editing (equal). **Amineh Koravand:** Conceptualization (equal); Formal Analysis (supporting); Funding Acquisition (supporting); Methodology (equal); Project administration (supporting); Resources (equal); Supervision (lead); Writing - Original Draft Preparation (equal); Writing – review and editing (equal).

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9. Data availability statement

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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Supplemental Materials

Table 3. ANOVA and t-test results for ITPC and power values in the quiet conditions.

ITPC			**Adults**					**Children**		
	df	t	p≤	*d*		df	t	p≤	*d*
Theta and Alpha frequency range									
Paired sample t-tests									
T7-Cz	14	0.831	0.42	0.215		14	6.8	<.001	1.756
T8-Cz	14	0.844	0.413	0.218		14	3.024	0.005	0.781
T7-T8	14	1.79	0.095	0.462		14	1.935	0.037	0.5
Beta and Gamma frequency range									
	df (between groups)	df (within groups)	F	p≤	η2	df (between groups)	df (within groups)	F	p≤	η2
Stimulus (S)	1	14	0.235	0.635	0.016	1	14	6.605	0.022	0.321
Electrode (E)	2	28	2.305	0.118	0.141	2	28	50.312	<0.001	0.782
S × E	2	28	1.918	0.166	0.121	2	28	25.480	<0.001	0.645
Paired sample t-tests		df	t	p≤	*d*		Tonal		Verbal	
Verbal-tonal		14	0.485	0.635	0.125	T7-Cz	t= 7.119, p <.001, d = 1.838		t= 4.872, p<.001, d= 1.258	
T7-Cz		14	0.057	0.956	0.410	T8-Cz	t= 10.693, p<0.01, d= 2.761		t= 3.238, p= .006, d= .836	
T8-Cz		14	1.586	0.135	0.015	T7-T8	t= 2.516, p=.025, d= .650		t= .346, p= .735, d= .089	
T7-T8		14	2.154	0.049	0.556		df	t	p≤	*d*
						T7 T-V	14	2.392	0.031	0.618
						Cz T-V	14	3.347	0.005	0.864
						T8 T-V	14	4.961	<.001	1.281

Power

Theta and Alpha frequency range								
	Adults				**Children**			
Paired sample t-tests	df	t	p≤	*d*	df	t	p≤	*d*
Verbal-tonal	14	0.035	0.973	0.009	14	2.545	0.023	0.657
T7-Cz	14	0.507	0.62	0.131	14	2.952	0.011	0.762
T8-Cz	14	2.201	0.045	0.568	14	3.671	0.003	0.948
T7-T8	14	4.478	<.001	1.221	14	0.059	0.954	0.015

Table 4. ANOVA and t-test results for the ta- and bg- ITPC values in the noise conditions.

	T7					Cz					T8				
	df (between gr oups)	df (within gr oups)	F	p≤	η^2	df (between gr oups)	df (within gr oups)	F	p≤	η^2	df (between gr oups)	df (within gr oups)	F	p≤	η^2
Theta and Alpha frequency range															
(1) Stimulus × Noise × SNR × Group × Electrode															
Stimulus (S)	1	28	0.683	0.416	0.024	1	28	2.579	<.001	0.424	1	28	6.482	0.017	0.188
Noise (N)	1	28	31.373	<.001	0.528	1	28	14.623	<.001	0.343	1	28	49.297	<.001	0.638
Signal to noise ratio (SNR)	2	56	13.677	<.001	0.328	2	56	4.236	0.019	0.131	2	56	18.989	<.001	0.404
Group (G)	1	28	14.355	<.001	0.339	1	28	3.454	0.074	0.110	1	28	8.929	0.006	0.242
SNR × G	2	56	0.981	0.381	0.034	2	56	0.625	0.539	0.022	2	56	2.583	0.085	0.084
SNR × S	1.617	45.277	0.723	0.463	0.025	1.49	41.724	1.781	0.178	0.060	2	56	2.093	0.133	0.070
SNR × N	2	56	2.243	0.116	0.074	2	56	0.577	0.565	0.020	2	56	13.203	<.001	0.320
S × G	1	28	0.335	0.567	0.012	1	28	0.033	0.857	0.001	1	28	0.289	0.595	0.010
S × N	1	28	6.781	0.015	0.195	1	28	2.548	0.122	0.083	1	28	0.926	0.344	0.032
N × G	1	28	6.455	0.017	0.187	1	28	3.834	0.06	0.12	1	28	2.655	0.114	0.087
S × SNR × G	2	56	2.396	0.1	0.079	2	56	0.293	0.747	0.010	2	56	6.843	0.002	0.196
SNR × N × G	2	56	1.061	0.353	0.037	2	56	2.309	0.109	0.076	2	56	6.623	0.003	0.191
S × N × SNR	2	56	0.758	0.473	0.026	1.58	44.235	1.088	0.333	0.037	2	56	18.588	<.001	0.399
S × N × SNR × G	2	56	4.540	0.015	0.140	2	56	0.244	0.784	0.009	2	56	7.268	0.002	0.206
	Tonal			Verbal							Tonal			Verbal	
Noise (N)	F = 8.008, p = .009, η^2= .222			F = 29.387, p = <.001, η^2= .512							F = 19.385, p = <.001, η^2= .409			F = 3.427, p = <.001, η^2 = .521	
Signal to noise ratio (SNR)	F = 3.568, p = .035, η^2= .113			F = 8.911, p = .001, η^2= .241							F = 6.963, p = .002, η^2= .199			F = 11.647, p = <.001, η^2= .294	
Group (G)	F = 11.066, p = .002, η^2= .283			F = 7.906, p = .009, η^2= .220							F = 4.149, p = .051, η^2= .129			F = 9.629, p = .004, η^2= .256	
SNR × G	F = 2.935, p = .061, η^2= .095			F = .740, p = .482, η^2= .026							F = 1.715, p = .189, η^2= .058			F = 6.018, p = .004, η^2= .177	
SNR × N	F = .535, p = .588, η^2= .019			F = 2.607, p = .083, η^2= .085							F = .859, p = .429, η^2= .030			F = 24.806, p = <.001, η^2= .470	
N × G	F = 2.794, p = .106, η^2= .091			F = 4.589, p = .041, η^2= .141							F = 3.431, p = .075, η^2= .109			F = .240, p = .628, η^2= .009	
SNR × N × G	F = 4.257, p = .019, η^2= .132			F = 1.012, p = .370, η^2= .035							F = .754, p = .475, η^2= .026			F = 1.535, p = <.001, η^2= .273	
	Tonal × Babble		Tonal × White									Verbal × Babble		Verbal × White	
Signal to noise ratio (SNR)	F = 2.273, p = .125, η^2= .075		F = 1.810, p = .173, η^2= .061									F = 37.766, p = <.001, η^2= .574		F = 1.422, p = .250, η2 = .048	
Group (G)	F = 12.543, p = .001, η^2= .309		F = 7.436, p = .011, η^2= .210									F = 6.360, p = .018, η^2= .185		F = 111.477, p = .002, η^2= .291	
SNR × G	F = 1.329, p = .273, η^2= .045		F = 6.308, p = .003, η^2= .184									F = 16.563, p = <.001, η^2= .372		F = 1.142, p = .327, η^2 = .039	
Independant t-tests															
+10 dB SNR			t = 2.081, p = .047, d = .760		Babble	t = 3.036, p = .005, d = 1.109					+10 dB SNR	t = 2.595, p = .016, d = .947			
+5 dB SNR			t = 1.830, p = .078, d = .668		White	t = 2.017, p = .053, d = .736					+5 dB SNR	t = 4.633, p <.001, d = 1692			
0 dB SNR			t = 3.693, p <.001, d = 1.348								0 dB SNR	t = .210, p = .835, d = .077			
Beta and Gamma frequency range															
Stimulus (S)	1	29	3.646	0.066	0.112	1	29	1.988	0.002	0.275	1	29	9.876	<.001	0.758
Noise (N)	1	29	85.381	<.001	0.746	1	29	41.531	<.001	0.589	1	29	143.296	<.001	0.832
Signal to noise ratio (SNR)	2	58	8.111	<.001	0.219	2	58	7.230	0.002	0.200	2	58	25.808	<.001	0.471
SNR × S	2	58	2.176	0.123	0.070	2	58	1.787	0.177	0.058	2	58	0.655	0.523	0.022
SNR × N	2	56	0.033	0.967	0.001	2	58	6.503	0.003	0.183	2	58	27.458	<.001	0.486
S × N	1	29	2.662	0.114	0.084	1	29	12.820	0.001	0.307	1	29	0.525	0.475	0.018
S × N × SNR	2	58	1.938	0.153	0.063	2	58	3.692	0.031	0.113	2	58	58.206	<.001	0.667
						Tonal			Verbal		Tonal			Verbal	
Noise (N)						F = 15.805, p <.001, η^2= .353			F = 3.172, p = <.001, η^2= .510		F = 66.921, p = <.001, η^2= .698			F = 6.337, p <.001, η^2= .675	
Signal to noise ratio (SNR)						F = 1.802, p = .174, η^2= .058			F = 6.967, p = .002, η^2= .194		F = 18.347, p = <.001, η^2= .387			F = 12.113, p <.001, η^2= .295	
SNR × N						F = .475, p = .624, η^2= .016			F = 9.145, p = <.001, η^2= .240		F = 7.181, p = .002, η^2= .198			F = 47.088, p <.001, η^2= .619	
Paired sample T-tests							Verbal × Babble	Verbal × White			Babble	White		Babble	White
+10 and + 5 dB SNR							t = .332, p = .742, d = .061	t = 3.851, p = <.001, d = .703			t = .583, p = .564, d = .106	t = 3.004, p = .005, d = .548		t = 2.790, p = .009, d = .509	t = .232, p = .818, d = .042
+10 and 0 dB SNR							t = .316, p = .754, d = .058	t = 4.026, p = <.001, d = .735			t = 2.014, p = .053, d = .368	t = 5.989, p <.001, d = 1.093		t = 8.994, p <.001, d = 1.642	t = 4.364, p <.001, d = .797
+5 and 0 dB SNR							t = .671, p = .507, d = .123	t = 1.325, p = .195, d = .242			t = 2.591, p = .015, d = .473	t = 3.696, p <.001, d = .675		t = 7.882, p <.001, d = 1.439	t = 3.406, p = .002, d = .622

Table 5. ANOVA and t-test results for the ta- and bg- power values in the noise conditions.

Theta and Alpha frequency range

(1) Stimulus × Noise × SNR × Electrode

	T7					Cz					T8				
	df (between groups)	df (within groups)	F	p≤	η^2	df (between groups)	df (within groups)	F	p≤	η^2	df (between groups)	df (within groups)	F	p≤	η^2
Stimulus (S)	1	29	2.919	0.98	0.091	1	29	0.632	0.433	0.021	1	29	11.883	0.002	0.291
Noise (N)	1	29	1.174	0.288	0.039	1	29	0.47	0.499	0.016	1	29	16.044	<0.001	0.356
Signal to noise ratio (SNR)	2	58	0.313	0.732	0.011	1557	45.167	0.487	0.571	0.017	2	58	4.827	0.012	0.143
SNR × S	2	58	0.661	0.52	0.022	2	58	0.682	0.51	0.023	2	58	0.403	0.67	0.014
SNR × N	2	58	0.269	0.765	0.009	2	58	1.677	0.196	0.055	2	58	0.679	0.511	0.023
S × N	1	29	1.619	0.213	0.053	1	29	1.682	0.205	0.055	1	29	2.317	0.139	0.074
S × N × SNR	2	58	0.531	0.591	0.018	2	58	1.993	0.145	0.064	2	58	2.77	0.071	0.087

(2) Stimulus × Noise × Group

	Verbal					Tonal				
	df (between groups)	df (within groups)	F	p≤	η^2	df (between groups)	df (within groups)	F	p≤	η^2
Noise (N)	1	28	4.63	0.04	0.142	1	28	6.209	0.019	0.181
Group (G)	1	28	0.386	0.54	0.014	1	28	5.833	0.21	0.175
N × G	1	28	0.272	0.606	0.01	1	28	7.155	0.012	0.204

Independant t-tests	df	t	p≤	d
Babble	28	3.008	0.006	1098
White	28	1.619	0.117	0.591

Beta and Gamma frequency range

(1) Stimulus × Noise × Group × Electrode

	T7					Cz					T8				
	df (between groups)	df (within groups)	F	p≤	η^2	df (between groups)	df (within groups)	F	p≤	η^2	df (between groups)	df (within groups)	F	p≤	η^2
Stimulus (S)	1	28	0.082	0.776	0.003	1	28	0.212	0.649	0.008	1	28	0.403	0.531	0.014
Noise (N)	1	28	0.019	0.892	0.001	1	28	0.351	0.558	0.012	1	28	2.402	0.132	0.079
Group (G)	1	28	1.382	0.25	0.047	1	28	6.403	0.017	0.186	1	28	0.555	0.463	0.190
S × G	1	28	4.445	0.044	0.137	1	28	0.944	0.34	0.033	1	28	0.235	0.632	0.008
S × N	1	28	1.899	0.179	0.064	1	28	0.204	0.655	0.007	1	28	0.072	0.79	0.003
N × G	1	28	0.213	0.648	0.008	1	28	0.002	0.967	0.000	1	28	1.242	0.275	0.042
S × N × G	1	28	2.612	0.117	0.085	1	28	0.044	0.835	0.002	1	28	8.596	0.007	0.235

	Tonal	Verbal
Noise (N)	F=2.117, p=0.157, η^2=0.070	F=0.654, p=0.426, η^2=0.023
Group (G)	F=0.049, p=0.827, η^2=0.002	F=0.866, p=0.360, η^2=0.030
N × G	F=10.665, p=0.003, η^2=0.276	F=1.392, p=0.248, η^2=0.047
Independant Sample test		
Babble	t=1.229, p=0.229, d=0.449	
White	t=-0.813, p=0.423, d=0.297	

3.3. Main experiment

3.3.1. Methodology

Following the pre-experiment results, parameters were chosen for the electrophysiological measures of the main experiment. As nonverbal and verbal stimuli had different configurations and interesting features in noise, both stimuli were kept. Only one type of noise was chosen: the white noise because it was less disruptive than the babble noise on the AEPs waveforms. For the SNR, 0 dB SNR was too disruptive and very few AEPs waveforms were present in children. The two others, +5- and +10-dB SNR, had better results, but sometimes they yielded similar results. The + 5 dB SNR was therefore selected and a more favourable +15 dB SNR condition replaced the +10 dB SNR as it is the recommended SNR for learning in children (see Shield et al., 2010 for a literature review). Moreover, with regard to the analysis and electrode selection, the comparison between three electrodes was selected as it yielded interesting results in Article 3. However as both ALRs and TFA analysis were conducted, central electrodes where fronto-central evoked potentials were prioritized as the T-complex, different from fronto-central P1-N1-P2-N2 is evoked at temporal electrodes. The comparison between different evoked potential amplitudes and latencies do not make sense. Moreover, only phase analysis was maintained as Article 3 shows that power analysis is not as affected by noise than phase analysis.

3.3.2. Article 4

Article 4 is in preparation.

Mild traumatic brain injury in school-aged children: Insights into auditory processing in noise using auditory evoked potentials. [Manuscript in preparation].

Title

Mild traumatic brain injury in school-aged children: Insights into auditory processing in noise using auditory evoked potentials

Declaration of interest

The authors have declared that no conflict of interest existed at the time of publication.

Type of paper

Research Paper

Abstract

Introduction: Mild traumatic brain injury (mTBI) has a detrimental global impact on children's functioning, affecting millions of them worldwide. Evaluating auditory processing through Auditory Evoked Potentials (AEPs) could help understand neurophysiological changes in auditory functions associated with mTBI. The aim of the current study was to identify a neuromarker of auditory dysfunction post-mTBI through AEPs in noise. *Methods:* Twenty-one school-aged children (eleven with mTBI) participated in the study. Auditory evoked responses were recorded with two types of stimuli (Verbal and Tonal) in quiet and noise (white noise at +5 and +15dB signal-to-noise ratio—SNR) at three electrode positions (C5-left, Cz-central, and C6-right) for two measure times. Mixed factorial ANOVAs were performed for amplitude and latency values of two AEPs responses, P1 and N2, and Intertrial phase coherence (ITPC) values calculated for the averaged time points from 100 to 400 msec for 4-12 and 13-60 Hz frequency ranges. *Results:* Only N2 latency at C6 was greater in controls than in mTBI participants. The effects of the stimulus, listening condition, and electrode were significant for both groups' peak amplitudes, latencies, and ITPC values. The smallest SNR and central electrode produced the smallest amplitudes, ITPC values, and most prolonged latencies. Moreover, the tonal stimulus produced the smallest ITPC values and amplitudes with the shortest latencies. *Discussion:* No definitive marker of auditory dysfunction post-mTBI could be found. Responses in noise were measured, indicating that they could be utilized to objectively auditory function in complex listening situations.

Keywords: mTBI, mild traumatic brain injury, ITPC, auditory evoked potentials, pediatric, EEG

1. Introduction

Worldwide, mild traumatic brain injury (mTBI) affects 55.9 million people yearly (Dewan et al., 2019). In children, this incidence varies between 185 and 865 cases per 100,000 children (Falk et al., 2009; Kraus, 1986; Kuitunen et al., 2023), of whom 70 to 90% fully recover (Dewan et al., 2016; Falk et al., 2009; Hawley et al., 2003; Kraus, 1986; Kuitunen et al., 2023; Quayle et al., 2014), generally within the first four weeks following the injury (Zemek et al., 2016). For the remaining children, the complex nature of these injuries contributes to the varied and heterogeneous symptomatology and impairments observed following the mTBI (Rosenbaum & Lipton, 2012). mTBI has been shown to be a serious injury with a multitude of possible lasting associated effects (Lumba-Brown et al., 2018). Recent literature has shown a growing body of evidence indicating the presence of auditory deficits post mTBI (Hoover et al., 2017; Kraus et al., 2016; Kraus & White-Schwoch, 2017, 2018; Krizman et al., 2023; Stahl et al., 2024; Thompson et al., 2018; Vander Werff, 2012; Vander Werff & Rieger, 2017, 2019b, 2019a). Central auditory processing difficulties following mTBI have been reported in adults (Hoover et al., 2017; Stahl et al., 2024; Turgeon et al., 2011; Vander Werff & Rieger, 2019a) and children (Thompson et al., 2018). However, it is possible that central auditory processing behavioural tests results can be altered in a subset of mTBI participants due to insufficient cognitive efforts when completing the tests rather than true auditory difficulties (Vander Werff & Rieger, 2019a). Auditory evoked potentials (AEPs) do not require active participation and could help identify mTBI-induced auditory difficulties. AEPs, specifically time-locked responses, were reviewed and promoted as an option to detect subtle impairment caused by mTBI in the auditory neural pathways (Vander Werff, 2012; Washnik et al., 2019).

AEPs, particularly Auditory Late Responses (ALRs) composed of the P1, N1, P2, and N2 wave peak components, can offer insights into cortical sound processing (Woods et al., 1987). Unfortunately, ALR results in adult with mTBI are conflicted. On the one hand, studies reported N1 (Gosselin et al., 2006; Stahl et al., 2024), P2 (Gosselin et al., 2006) and N2 (Solbakk et al., 1999) amplitude reductions in adults with mTBI compared to controls. On the other hand, in similar populations, studies indicated no differences in N1 and N2 amplitudes and latencies (Rugg et al., 1988, 1993). Vander Werff and Rieger (2019b)

investigated P1, N1 and P2 in quiet and noise in adults with mTBI using speech sounds and a 20-talker babble noise. They reported similar results between groups as P1, N1 and P2 latencies were elongated, and amplitudes were reduced in noise compared to quiet. An interaction between condition and group was recorded where the P2 amplitude was more reduced, and P1, N1 and P2 latencies were more elongated by noise only in adults with mTBI compared to controls (Vander Werff & Rieger, 2019b). Studies conducted only under quiet conditions offer, to some extent, contradictory information, as the impact of mTBI does not appear to affect the ALRs systematically. ALRs in noise show promising results and highlight a need to investigate ALRs in more challenging listening conditions. No mTBI studies have been reported with ALRs in children, but a study with brainstem frequency following responses indicated disrupted neural pathways in children with mTBI when compared to controls (Kraus et al., 2016).

As ALR results are limited and cannot provide always a clear picture of how mTBI can affect auditory processing, further investigation of EEG activity is warranted. Recorded with EEG, cortical oscillations or rhythmic voltage changes in brain activity underline different functions and brain states (Wang, 2010), and could provide additional avenues for exploring auditory processing following mTBI. Cortical oscillations have been shown to support auditory processes such as speech perception (Doelling et al., 2014; Von Stein & Sarnthein, 2000; Yellamsetty & Bidelman, 2018) or the encoding of acoustic features and speech representation (Shahin et al., 2010; Yellamsetty & Bidelman, 2018). Oscillatory activity has been quantified via phase components where the cortical oscillations' phase synchronization or Intertrial Phase Clustering (ITPC) has been correlated with ALRs (Bishop, Anderson, et al., 2011; Koerner & Zhang, 2015). In adults, auditory processing in noise with both ALRs and ITPCs was evaluated (Koerner & Zhang, 2015). ITPC noise values were correlated with ALRs amplitudes and latencies in noise (Koerner & Zhang, 2015). Finally, all reported studies evaluated ALRs or ITPC values in midline electrodes, which could ignore hemispheric asymmetries reported in other EEG studies following mTBI (Boshra et al., 2020; Desjardins et al., 2021; Liu et al., 2021; Virji-Babul et al., 2014). Although no known studies evaluating children with mTBI using ALRs or ITPCs in noise have been reported, adult literature promises that the combination of ALRs and

ITPC could help detect subtle auditory dysfunction following mTBI (Koerner & Zhang, 2015; Vander Werff & Rieger, 2019b).

The current investigation aimed to uncover neurophysiological markers of auditory dysfunction post-mTBI in challenging listening conditions using auditory neurophysiological measures: ALRs and phase synchronization (ITPC). More specifically, the study's goal was to document differences in ALRs responses and ITPC values elicited in quiet and noise between mTBI children compared to typically developing controls and if these differences changed over time.

2. Material and methods

2.1. Ethics

The current prospective cohort study with comparison complied with the ethics requirements of the University of Ottawa (H-07-20-5557), the Centre Hospitalier Universitaire (CHU) Sainte-Justine (MP-21-2020-2618), and the Pediatric committee of the McGill University Hospital Center (MEO-21-2023-9276). Parents gave written consent for participation, and children assented before each data collection appointment.

2.2. Participants

The current study recruited twenty-six school-aged children (same participants were also included in Duquette-Laplante et al., 2024). Five participants were excluded: three from the control group as they failed behavioural auditory processing tests (see exclusion criteria in the next section and reported in Duquette-Laplante et al., 2024) and two from the experimental group as one was diagnosed with intracranial bleeding and the other with attention deficit hyperactivity disorder (see exclusion criteria in the next section). Twenty-one children participated: eleven in the mTBI group (mean ± SD: 10.11 ± 1.39 years, nine boys) and ten aged- and sex-matched controls (mean ± SD: 10.12 ± 1.35 years, nine boys) (see Table 1). Participants with a mTBI were recruited from the emergency departments of the CHU Sainte-Justine and the Montreal Children's Hospital. Multiple procedures were employed to recruit children in the control group: the External Orthopedic Clinic of the

CHU Sainte-Justine, schools, recreational centers, sports organizations and word-of-mouth.

2.2.1. Inclusion/exclusion criteria

Participants included in the current study had French as a dominant language with normal hearing acuity in both ears (≤ 15 dB HL or lower for 0.25 to 8 kHz) (Northern & Downs, 2002) and normal middle ear function (static compliance between 0.3 and 2.5 cc and middle ear pressure between -150 and +50 daPa) (Northern & Downs, 2002). Children in the mTBI group were included if they experienced direct or indirect head trauma and received their first diagnosis of mTBI from a physician less than 14 days preceding their involvement in the study. Specifically, the children had to meet the Quebec, Canada diagnostic criteria for mTBI, which includes: (1) a Glasgow Coma Scale score of 13-15; (2) a loss of consciousness ≤30 minutes; (3) an alteration of consciousness ≤24 hours; (4) post-traumatic amnesia ≤1 day; and (5) if conducted, brain imaging results indicating the presence or absence of focal signs of injury (Truchon et al., 2018). Children in the control group were excluded if they failed one or more central auditory behavioural tests (reported in Duquette-Laplante et al., 2024). In both groups, children with difficulties in school, chronic middle ear infections (Borges et al., 2013; Gravel et al., 2006), ventilation tubes or ototoxic medications, an intellectual disability, a history of head injury, born prematurely (<37 weeks), or with the following health conditions were excluded: developmental disorders such as autism spectrum disorder, neurological disorders such as epilepsy, congenital conditions such as fetal alcohol syndrome, psychiatric disorders such as obsessive-compulsive disorder, metabolic conditions such as diabetes, attention or language disorders.

Table 1. mTBI participants' injury description and age of their sex-matched control

Characteristic	mTBI (n = 11)	Control (n = 10)
Age at initial testing (mean ± SD)	10.11 ± 1.39	10.12 ± 1.35
Female	2	1
French as a dominant language	11	10
mTBI injury		
Cause of Injury		
Fall	3	
Sports	6	
Assault	2	
Type		
Direct impact to the head	4	
Direct impact/head against object	2	
Fall ground level	3	
Fall >1 m (3 ft)	2	
Impact on the head		
Face	4	
Forehead	2	
Top of head	1	
Back of head	3	
No direct blow to the head	1	
Glasgow score		
15	10	
14	1	

2.3. Procedure

The current experiment was part of a larger project that included behavioural central auditory tests, questionnaires, and a cognitive screening (reported in Duquette-Laplante et al., 2024). Participants were assessed with electrophysiological measures. Children were seen twice. At Time 1 (T1), children in the mTBI group (mean ± SD: 10 ± 5 days) were assessed within 14 days of the injury and children in the control group were evaluated at a time when they could be matched to participants with mTBI in terms of age and sex. At Time 2 (T2), all participants (mean ± SD; mTBI: 116 ± 10 days; controls: 103 ± 11 days) were seen at least three months following T1.

2.4. Electrophysiological measures

2.4.1. Recording

The BrainVision actiCHAMP™ amplifier (BrainVision LLC), the Pycorder software (BrainVision LLC) on a first computer and a cap with 64 Ag/AgCl active electrodes placed according to the 10-20 system (Jasper, 1958; Klem, 1999) were used to record EEG. Oz was used as the online reference electrode, and the ground electrode was placed on the upper forehead (Fpz). Two electrodes, PO3 and PO4, were positioned below the eyes to control artifacts from vertical eye movements and blinking. Electrolyte gel was applied to each electrode until an impedance below 40 kΩ was achieved (Ferree et al., 2001; Mathewson et al., 2017). Recordings were sampled at a rate of 1000 Hz (Cohen, 2014). The participant was comfortably seated in a room treated to counter electromagnetic waves and noise. As they watched a muted movie of their choice, they were instructed to move as little as possible and stay calm and relaxed. Breaks were provided as needed by the participants during recording sessions. Each session lasted between 70 and 90 minutes, including cap/electrode preparation and recording.

2.4.2. Stimuli

Two types of stimuli were selected to evaluate auditory cortical processing in both quiet and noise: a speech sound (/da/) and a pure tone (1000 Hz). Both stimuli had a duration of 170 msec with a rise and fall time of 10 msec and were created with the Pratt synthesizer (Boersma & Weenink, 1992). Stimuli were calibrated with a sonometer (Larson Davis Laboratories model 800B) to an output of 70 dBA. A white noise, generated with the Audacity® software™, was calibrated with the sonometer (Larson Davis Laboratories model 800B) at 55 and 65 dBA levels, which corresponds to +15 and +5 dB SNRs for each stimulus. These levels were chosen based on previous literature to see differences between groups and listening conditions (Duquette-Laplante et al., 2024; Gustafson et al., 2019). Combining two stimuli, two listening conditions and two SNRs resulted in six conditions: two in quiet and four in noise. Each condition was presented in a block of 200 stimulations. The order of the six stimulus conditions was pseudorandomized between participants. Each block lasted between 4 minutes and 4 minutes, 15 seconds. The interstimulus interval was

a random jitter duration between 1130 and 1330 msec to avoid the possibility of predicting the arrival of the next stimulus and its impact on the evoked potential measurements (Cohen, 2014). The acquisition window (epoch) was set from -200 to 800 msec. Auditory stimuli were presented in both ears through a second computer with the Presentation® software (Neurobehavioral Systems Inc.) via insert earphones (E-A-RTONE 3A) connected to an audiometer (Madsen, Midimate 602).

2.4.3. Pre-processing

The analysis was performed in MATLAB version 2022b (The MathWorks Inc., 2022) with Fieldtrip (Oostenveld et al., 2010). To remove artifacts, EEG segments with an amplitude exceeding ± 100 μV were not included in the average data. After removing these EEG segments, the remaining segments were corrected with the Independent Component Analysis (ICA) method (Makeig et al., 1993) to extract eye movements from the signal. The trials were examined individually, and those containing stimulation artifacts were manually excluded. Overall, quiet conditions contained 180 ± 11 (mean ± SD) trials, and noise conditions contained 172 ± 15 (mean ± SD) trials.

A spatial filtering was applied to the EEG signal, going from the second derivative of the signal (Laplacian) to a radial current density (SCD for scalp current density) (Perrin et al., 1989). This modification reduces spatial interference between activity originating from nearby electrical sources and more distant sources across the scalp, facilitating the localization of the source of particular activities (Cohen, 2014; Pernier & Bertrand, 1997) (Cohen, 2014; Pernier & Bertrand, 1997).

2.4.4. Auditory Late Responses

Two independent judges identified the ALR components (P1-N1-P2-N2) on three separate electrodes (C5 - left, Cz - central, and C6 - right). The identification time windows varied according to the listening conditions. The judges followed two rules: (1) the most negative or positive wave component in the predetermined time windows based on previous studies (Benítez-Barrera et al., 2021; Bishop, Hardiman, et al., 2011; Duquette-Laplante et al., 2024; Gustafson et al., 2019) and on grand average waveforms – P1: children 60-150 ms,

N1: children 100-300 ms; P2: children 160-360 ms; N2: children 180-400 ms, and (2) challenging identification was completed comparing the difficult waves to their related responses: same stimulus and electrode, but different listening condition. For example, if the response at the central electrode for the tonal stimulus with the +5 dB SNR white noise was difficult to identify, both the response at the central electrode for the tonal stimulus in quiet and with the +15 dB SNR were reviewed to help identify the wave peak components. If discrepancies occurred, a discussion between judges took place to reach an agreement. The inter-judge agreement was 79% for all wave components. To proceed with condition analysis, a maximum of three missing wave-peak components per group were allowed. The missing components were replaced with the group's mean.

2.4.5. Time-Frequency analysis

To ensure a representative sample and to mitigate the effects of the variability in trial numbers, 100 individual trials per participant per condition were randomly selected from the artifact-free data set for time-frequency analyses. Time-frequency analyses were performed using the convolution of the EEG signal and a set of complex Morlet wavelets, defined as complex sinusoidal waves filtered by a Gaussian function. The wavelet frequencies ranged from 2 Hz to 100 Hz with a 0.5 Hz interval. Wavelet cycles (m) varied between 2 and 15.

2.4.5.1. ITPC

The timing and consistency of the timing of phase values over EEG trials were then analyzed using the ITPC measure:

$$\mathrm{ITPC_{tf}} = \left| n^{-1} \sum_{r=1}^{n} e^{ik_{tfr}} \right|$$

Where e^{ik} provides the complex polar representation of a phase angle k for trial r at a specific time-frequency point tf (Cohen, 2014), the ITPC value ranges from 0 to 1, representing the absence of synchronization and perfect synchronization of the signal phase between trials, respectively. Three electrodes, C5- left, Cz- central, and C6- right, were

selected based on previous studies (Bishop, Hardiman, et al., 2011; Duquette-Laplante et al., 2024; Tonnquist-Uhlen et al., 2003). A 300 msec time window from 100 to 400 msec post stimuli was selected (Bishop, Hardiman, et al., 2011; Duquette-Laplante et al., 2024; Gustafson et al., 2019; Shahin et al., 2010). Frequencies between 4 and 60 Hz, corresponding to the theta, alpha, beta and low gamma bands ranges, are generally reported to be involved in the auditory processing (Bishop, Hardiman, et al., 2011; Koerner & Zhang, 2015; Shahin et al., 2010; Vanvooren et al., 2015; Yellamsetty & Bidelman, 2018; Yordanova & Kolev, 2009). For the analysis, the four frequency bands were separated into two frequency category ranges, theta and alpha into the ta-ITPC range and beta and low gamma into the bg-ITPC range. Due to the small ISI and epoch, the frequencies corresponding to the delta band (0.5-4 Hz) could not be analyzed. The ITPC values were extracted and averaged across time points and frequencies into the two frequency categories.

2.5. Statistical analysis

Mixed factorial ANOVAs, performed with SPSS (version 29), were utilized to explore differences between five factors: one inter-subject factor: Group (2 levels: mTBI, control) and four intra-subject factors: Time (2 levels: T1 and T2), Stimulus (2 levels: Tonal and Verbal), Listening Condition (3 levels: Quiet, +15 dB SNR and +5 dB SNR) and Electrode (3 levels: C5- left, Cz- central and C6- right) on the latency and amplitude of the ALR wave components P1 and N2 as well as ITPC values for ta-ITPC and bg-ITPC. The threshold of significance was delineated at $p<0.05$. Greenhouse-Geisser corrections were reported when data sphericity was violated. For post hoc t-test analyses, a Bonferroni correction factor was applied, and Cohen's d was calculated. Levene's test for equality of variances was utilized when variance equality was not met.

3. Results

3.1.Time-locked analysis (ALR)

The results from the five-way mixed factorial ANOVAs with the factors Time (T1, T2), Stimulus (Verbal, Tonal), Listening Condition (Quiet, +15 dB SNR, +5 dB SNR),

Electrode (Left, Central, Right) and Group (mTBI, Control) for P1 and N2 amplitude and latency values are presented in Table 2 and summarized below (see Supplementary materials for amplitude and latency values in Tables 5 and 6 and detailed ANOVA decompositions in Tables 8 and 9). As seen in Figure 1, for mTBI and controls, N1 and P2 waves were mainly absent or in the early stages of development across different conditions. At the same time, P1 and N2 were present in at least seven or eight participants in each group for all listening conditions at all electrodes. Therefore, only P1 and N2 amplitude and latency were analyzed.

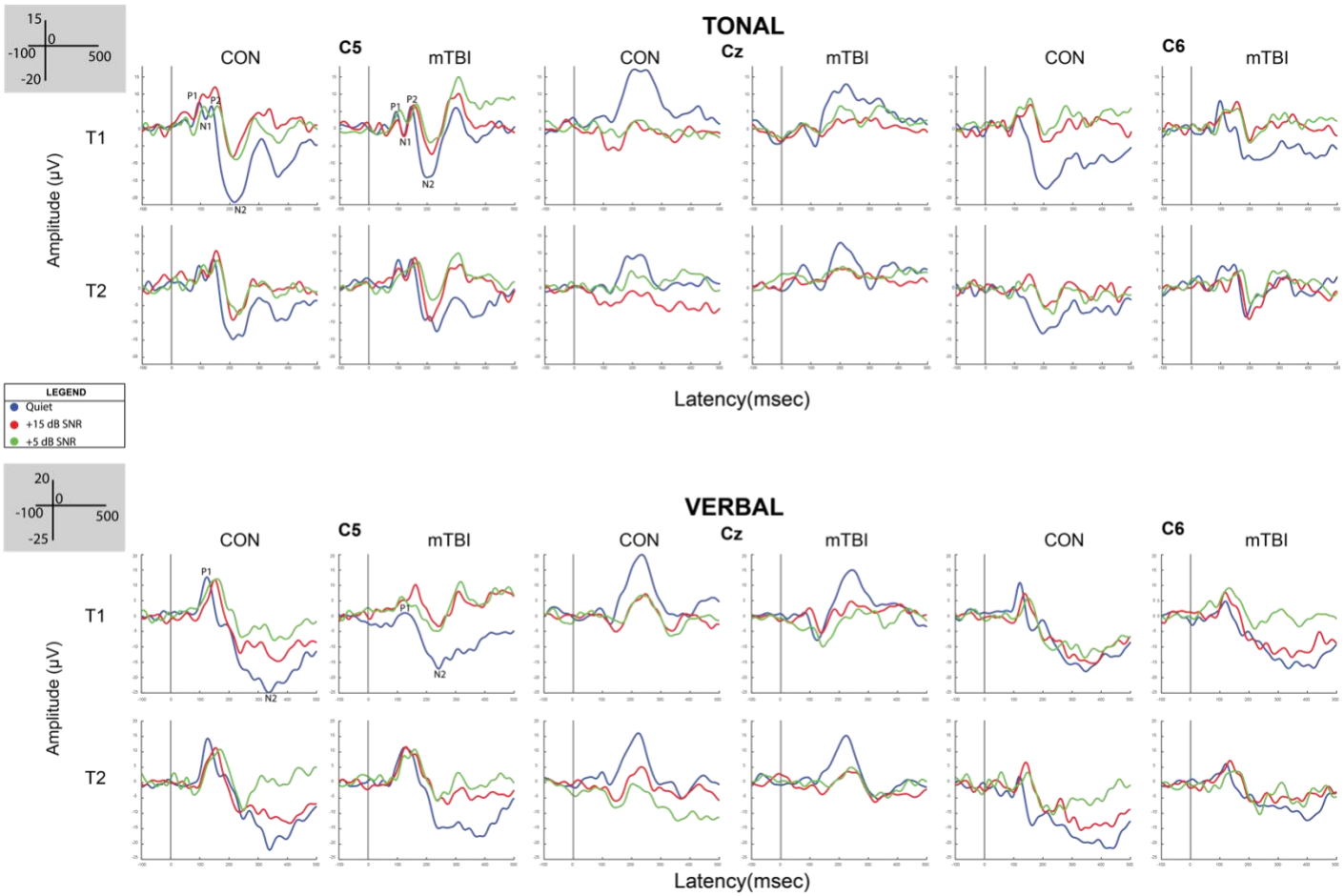

Figure 1. Grand averages of auditory late responses in mTBI children and their controls for three electrodes (C5, Cz and C6) in the three listening conditions (Quiet, +15 dB SNR and +5 dB SNR) with a verbal /da/ stimulus and a pure tone 1000 Hz stimulus, at two measure times (T1 and T2).

Table 2. Mixed factorial ANOVA results for P1 and N2 amplitude and latency.

ALR	Amplitude					Latency				
	df (between groups)	df (within groups)	F	p≤	η2	df (between groups)	df (within groups)	F	p≤	η2
P1										
Time (T)	1	19	0.172	0.683	0.009	1	19	0.333	0.57	0.017
Stimulus (S)	1	19	0.161	0.693	0.008	1	19	0.818	0.377	0.041
Electrode (E)	1.909	36.277	18.679	**<.001**	0.496	2	38	0.607	0.55	0.031
Listening Condition (LC)	1.643	31.219	4.62	**0.023**	0.196	1.874	35.61	201.641	**<.001**	0.914
Group (G)	1	19	0.725	0.405	0.037	1	19	0.204	0.657	0.011
T × G	1	19	1.792	0.196	0.086	1	19	3.622	0.072	0.16
S × G	1	19	0.078	0.784	0.004	1	19	0.02	0.888	0.001
LC × G	2	38	0.968	0.389	0.048	2	38	0.114	0.892	0.006
E × G	2	38	0.08	0.923	0.004	2	38	1.876	0.167	0.09
T × S	1	19	0.053	0.82	0.003	1	19	0.956	0.341	0.048
T × S × G	1	19	0.256	0.618	0.013	1	19	1.639	0.216	0.079
T x LC	2	38	0.206	0.815	0.011	2	38	0.366	0.696	0.019
T × LC × G	1.872	35.573	3.392	**0.048**	0.151	2	38	0.122	0.885	0.006
S × LC	2	38	0.957	0.393	0.048	2	38	1.16	0.324	0.058
S × LC × G	2	38	1.291	0.287	0.064	2	38	0.345	0.711	0.018
T × S × LC	2	38	0.085	0.919	0.004	2	38	0.74	0.484	0.037
T × S × LC × G	2	38	1.741	0.189	0.084	1	38	0.74	0.4	0.037
T × E	2	38	1.849	0.171	0.089	2	38	1.998	0.15	0.095
T × E × G	2	38	2.126	0.133	0.101	2	38	2.947	0.065	0.134
S × E	2	38	1.114	0.339	0.055	2	38	1.264	0.294	0.062
S × E × G	2	38	0.438	0.649	0.023	1.579	29.999	5.616	**0.007**	0.228
T × S × E	2	38	1.29	0.287	0.064	2	38	0.473	0.627	0.024
T × S × E × G	2	38	1.528	0.23	0.074	2	38	2.487	0.097	0.116
LC × E	4	76	2.421	0.056	0.113	3.104	58.979	4.009	**0.005**	0.174
LC × E × G	4	76	1.309	0.274	0.064	3.104	58.979	2.825	**0.031**	0.129
T × LC × E	4	76	0.616	0.652	0.031	4	76	0.43	0.787	0.022
T × LC × E × G	4	76	1.609	0.181	0.078	4	76	2.077	0.092	0.099
S × LC × E	4	76	0.62	0.65	0.032	3.035	57.669	2.867	**0.029**	0.131
S × LC × E × G	4	76	0.745	0.564	0.038	4	76	1.299	0.278	0.064
T × S × LC × E	4	76	0.763	0.553	0.039	2.924	55.557	0.021	**0.037**	0.139
T × S × LC × E × G	4	80.63	3.332	**0.014**	0.149	4	76	0.552	0.698	0.028
N2										
Time (T)	1	19	1.875	0.187	0.09	1	19	1.201	0.287	0.059
Stimulus (S)	1	19	5.385	**0.032**	0.221	1	19	67.536	**<.001**	0.78
Listening Condition (LC)	1.8	34.193	28.176	**<.001**	0.597	1.509	28.673	75.039	**<.001**	0.798
Electrode (E)	1.507	28.63	10.477	**<.001**	0.355	1.64	31.153	83.205	**<.001**	0.814
Group (G)	1	19	1.35	0.26	0.066	1	19	24.827	**<.001**	0.566

T × G	1	19	0.096	0.76	0.005	1	19	0.72	0.407	0.037
S × G	1	19	0.021	0.887	0.001	1	19	10.95	**0.004**	0.366
LC × G	2	38	0.518	0.6	0.027	2	38	0.5	0.61	0.026
E × G	2	38	0.724	0.492	0.037	1.64	31.153	3.771	**0.042**	0.166
T × S	1	19	0.373	0.548	0.019	1	19	1.168	0.293	0.058
T × S × G	1	19	0.003	0.959	0	1	19	0.405	0.532	0.021
T × LC	2	38	1.839	0.173	0.088	2	38	0.333	0.719	0.017
T × LC × G	2	38	2.425	0.102	0.113	2	38	0.093	0.912	0.005
S × LC	2	38	2.958	0.064	0.135	1.688	32.068	7.005	**0.003**	0.269
S × LC × G	2	38	0.806	0.454	0.041	2	38	2.544	0.092	0.118
T × S × LC	2	38	1.621	0.211	0.079	2	38	0.121	0.886	0.006
T × S × LC × G	2	38	1.839	0.173	0.088	2	38	0.576	0.567	0.029
T × E	2	38	0.016	0.984	0.001	1.729	32.859	3.411	0.051	0.152
T × E × G	2	38	1.345	0.273	0.066	1.729	32.859	4.76	**0.019**	0.2
S × E	2	38	0.967	0.389	0.048	1.996	37.922	4.365	**0.02**	0.187
S × E × G	2	38	2.239	0.12	0.105	1.996	37.922	4.137	**0.024**	0.179
T × S × E	2	38	0.362	0.699	0.019	2	38	1.566	0.222	0.076
T × S × E × G	2	38	0.729	0.489	0.037	2	38	2.194	0.125	0.104
LC × E	3.086	58.632	18.846	**<.001**	0.498	4	76	1.132	0.348	0.056
LC × E × G	4	76	1.966	0.108	0.094	4	76	2.414	0.056	0.113
T × LC × E	4	76	1.676	0.164	0.081	4	76	0.862	0.491	0.043
T × LC × E × G	4	76	0.52	0.721	0.027	4	76	0.289	0.884	0.015
S × LC × E	3.212	61.027	3.068	**0.031**	0.139	4	76	2.335	0.063	0.109
S × LC × E × G	3.212	61.027	3.129	**0.029**	0.141	4	76	0.559	0.693	0.029
T × S × LC × E	4	76	2.497	**0.05**	0.116	2.955	56.138	2.823	**0.048**	0.129
T × S × LC × E × G	2.951	56.078	2.583	**0.033**	0.12	4	76	2.177	0.08	0.103

3.1.1. Amplitude

For P1 and N2, the main 5-factor interaction Time × Stimulus × Listening Condition × Electrode × Group was significant [P1: $F(4,80.63) = 3.332$, $p = .014$, $\eta^2 = .149$; N2: $F(2.951,56.078) = 2.583$, $p = .033$, $\eta^2 = .12$]. Further statistical analysis of the Time × Listening Condition × Electrode × Group under the Stimulus factor was conducted.

3.1.1.1.Tonal stimulus

For the P1 amplitude, only the main effects of the Listening Condition factor [$F(2,38) = 4.484$, $p = .018$, $\eta^2 = .191$] and the Electrode factor [$F(2,38) = 19.915$, $p < .001$, $\eta^2 = .512$]

were significant. Further analysis revealed that no pairwise comparisons were significant for the Listening Condition factor [all conditions: $t < 1.523$, *ns*]. For the Electrode factor, both the left and right electrodes had greater amplitudes than the central electrode [C5 and C6 vs. Cz: $t > 2.923$, $p_{bonferroni} < .017$, $d > .637$] but were not significantly different from each other [C5 vs. C6: $t = .035$, *ns*].

For N2 amplitude, the effect of Group was not significant. However, the significant 3-factor interaction Time × Listening condition × Electrode [$F(3.071,58.341) = 2.786$, $p = .047$, $\eta^2 = .128$] was significant and further analysed under the Electrode factor. For the left and central electrodes, only the main effect of Listening Condition was significant [C5: $F(2,40) = 20.988$, $p < .001$, $\eta^2 = .128$; Cz: $F(2,40) = 6.336$, $p = .004$, $\eta^2 = .241$]. For the left electrode, the quiet condition yielded greater amplitude values than both noise conditions [Quiet vs. +15 and +5: $t > 4.393$, $p_{bonferroni} < .001$, $d > .958$; +15 vs +5: $t = 1.695$, *ns*]. For the central electrode, the greatest SNR had the greatest amplitude value [+15 vs Quiet and +5: $t > 2.620$, $p_{bonferroni} < .017$, $d > .5.71$; Quiet and +5: $t = .351$, *ns*]. Further analysis of the right electrode revealed no significant differences between listening conditions and between time [$t < 2.189$, $p_{bonferroni} > .040$, $d < .478$].

3.1.1.2. Verbal stimulus

For the P1 amplitude, the interaction Time × Listening Condition × Electrode × Group was significant [$F(4,76) = 2.62$, $p = .041$, $\eta^2 = .121$]. Further analysis revealed no significant differences between groups. Only the effect of Time with the +5 dB SNR at the left electrode was significant [$F(1,19) = 4.63$, $p = .044$, $\eta^2 = .196$] as P1 amplitude at T1 was greater than P1 amplitude at T2.

For N2 amplitude, two 3-factor interactions were significant: Listening Condition × Electrode × Group [$F(4,76) = 3.591$, $p = .01$, $\eta^2 = .159$] and Time × Listening Condition × Group [$F(2,38) = 3.702$, $p = .034$, $\eta^2 = .163$]. Further statistical analysis of the Listening Condition × Group interaction under the Electrode factor was conducted. There were no differences between groups for any of the three electrodes [C5: $t < 1.151$, *ns*; Cz: $t < 1.911$, *ns*; C6: $F < 1.581$, *ns*]. In the right electrode, the Listening Condition factor was significant, but further pairwise comparisons did not reveal significant differences between conditions [all conditions: $t < 1.530$, *ns*]. For the second significant interaction, Time × Group, was

decomposed under the Listening Condition factor. Results revealed no significant results for the main effects of Time or Group or their interaction for each listening condition [t < 1.308, *ns*].

3.1.2. Latency

For both wave peak components P1 and N2, the 5-factor interaction Time × Stimulus × Listening Condition × Electrode × Group was not significant [P1: $F(4, 76) = .552$, $p = .698$, $\eta^2 = .028$; N2: $F(4,76) = 2.177$, $p = .08$, $\eta^2 = .103$].

3.1.2.1. P1 wave component

For P1 latency, the Group factor was not significant, but the four-factor interaction Time × Stimulus × Listening Condition × Electrode [$F(4,76) = 3.065$, $p = .021$, $\eta^2 = .139$] was significant. Further analysis of the Time × Listening Condition × Electrode under the Stimulus factor was conducted. For the tonal stimulus, the Listening Condition × Electrode [$F(4,80) = 6.288$, $p < .001$, $\eta^2 = .239$] interaction was significant. Further analysis of the Listening Condition factor under the Electrode factor was conducted. P1 latency was the shortest in the quiet condition, then +15 dB SNR and the longest at +5 dB SNR [C5, all conditions: $t > 3.843$, $p_{bonferroni} < .017$, $d > .839$; Cz, all conditions: $t > 3.744$, $p_{bonferroni} < .017$, $d > .816$; C6, all conditions: $t > 3.347$, $p_{bonferroni} < .017$, $d > .730$]. For the verbal stimulus, only the main effect of the Listening Condition factor was significant [$F(2,40) = 92.084$, $p < .001$, $\eta^2 = .822$]. P1 latency was the shorter in more favourable listening conditions (Quiet < +15 dB SNR < +5 dB SNR) [all conditions: $t > 4.475$, $p_{bonferroni} < .017$, $d > .996$].

3.1.2.2. N2 wave component

There was two significant 3-factor interactions involving the Group factor: Time × Electrode × Group [$F(2,38) = 3.411$, $p = .014$, $\eta^2 = .200$] and Stimulus × Electrode × Group [$F(2,38) = 4.137$, $p = .024$, $\eta^2 = .179$]. The Time × Group interaction was analysed under the Electrode factor. Results revealed that for the left electrode, only the main effect of Time was significant where T1 latencies were shorter than T2 latencies [$F(1,19) = 4.689$, $p = .043$, $\eta^2 = .198$]. For the central electrode, pairwise comparisons revealed that the N2 latency of the mTBI group was significantly shorter than that of the control group at T1

only [T1: $t(19) = 2.682$, $p = .015$, $d = 1.172$; T2: $t = 0.087$, *ns*]. For the right electrode, only the main effect of Group [$F(1,19) = 1.700$, $p < .001$, $\eta^2 = .586$] was significant, with the control groups having longer N2 latency values than the group with mTBI.

The significant Stimulus × Electrode × Group interaction was decomposed under the Stimulus factor. For the tonal stimulus, the main effect of Group was significant [$F(1,19) = 5.388$, $p = .032$, $\eta^2 = .221$] where the control group had N2 latency longer than the group with mTBI. The main effect of Electrode [$F(2,38) = 73.020$, $p < .001$, $\eta^2 = .794$] was also significant. Pairwise comparisons revealed that the right and left electrodes had short latencies relative to the central electrode [C5 and C6 vs. Cz: $t > 8.914$, $p_{\text{bonferroni}} < .017$, $d > 1.944$; C5 vs. C6: $t = 1.562$, *ns*]. For the verbal stimulus, the interaction between the Electrode and Group factors revealed that the control group had longer N2 latencies than the group with mTBI for the right electrode only [C5: $t(19) = -6.133$, $p < .001$, $d = 2.680$; Cz and C6: $t < 2.230$, *ns*].

For N2 latency, there was also a significant four-factor interaction not involving the Group factor: Time × Stimulus × Listening Condition × Electrode [$F(4,80) = 2.611$, $p = .041$, $\eta^2 = .115$]. Further analysis was completed under the Stimulus factor. For the tonal stimulus, only the main effects of Listening Condition [$F(2,40) = 41.055$, $p < .001$, $\eta^2 = .672$] and Electrode [$F(2,40) = 74.646$, $p < .001$, $\eta^2 = .789$] were significant. Pairwise comparisons for the Listening Condition factor indicated that N2 latency was the shortest in the quiet condition and at the longest in the most unfavourable noise condition (Quiet < +15 dB SNR < +5 dB SNR) [all condition: $t > 4.258$, $p_{\text{bonferroni}} > .017$, $d < .928$]. For the Electrode factor, N2 latency was significantly longer at the central electrode than at the left and right electrodes [C5 and C6 vs. Cz: $t > 8.914$, $p_{\text{bonferroni}} > .017$, $d < .1.944$; C5 vs. C6: $t = 1.562$, *ns*].

For the verbal stimulus, the Listening Condition × Electrode interaction was significant [$F(4,80) = 2.624$, $p = .041$, $\eta^2 = .116$]. Pairwise comparisons revealed that for the left electrode, the only significant difference was between the quiet and the smallest SNR (+5) condition where N2 latency of the quiet condition was significantly shorter [Quiet vs. +5: $t(20) = 3.786$, $p_{\text{bonferroni}} = .001$, $d = .826$; +15 vs. Quiet and +5: $t < 1.668$, *ns*]. For both central and right electrodes, N2 latency was the shortest in the quiet condition, followed by the noise condition at +15 dB SNR and finally by the noise condition at +5 dB SNR [Cz,

all conditions: $t > 3.548$, $p_{bonferroni} > .017$, $d < .739$; C6, all conditions: $t > 5.961$, $p_{bonferroni} > .017$, $d < 1.300$].

3.2.Phase synchronization analysis (ITPC)

The results from the five-way mixed factorial ANOVAs with the factors Time (T1, T2), Stimulus (Verbal, Tonal), Listening Condition (Quiet, +15 dB SNR, +5 dB SNR), Electrode (Left, Central, Right) and Group (mTBI, Control) for each frequency category range (ta-ITPC and bg-ITPC) are presented in Table 3 and summarized below (see Supplementary materials for ITPC values in Table 7 and detailed ANOVA decompositions in Table 10). Time-frequency topoplots of the group with mTBI and the control group for the three listening conditions at the two measure times are presented in Figure 2. The neural oscillation frequencies are between 4 and 60 Hz, while the time window is averaged from 100 to 400 seconds. Both groups showed similar ITPC responses in quiet and in noise, where the verbal stimulus was more resistant to the noise, and smaller SNRs had a greater desynchronization effect on ITPC values.

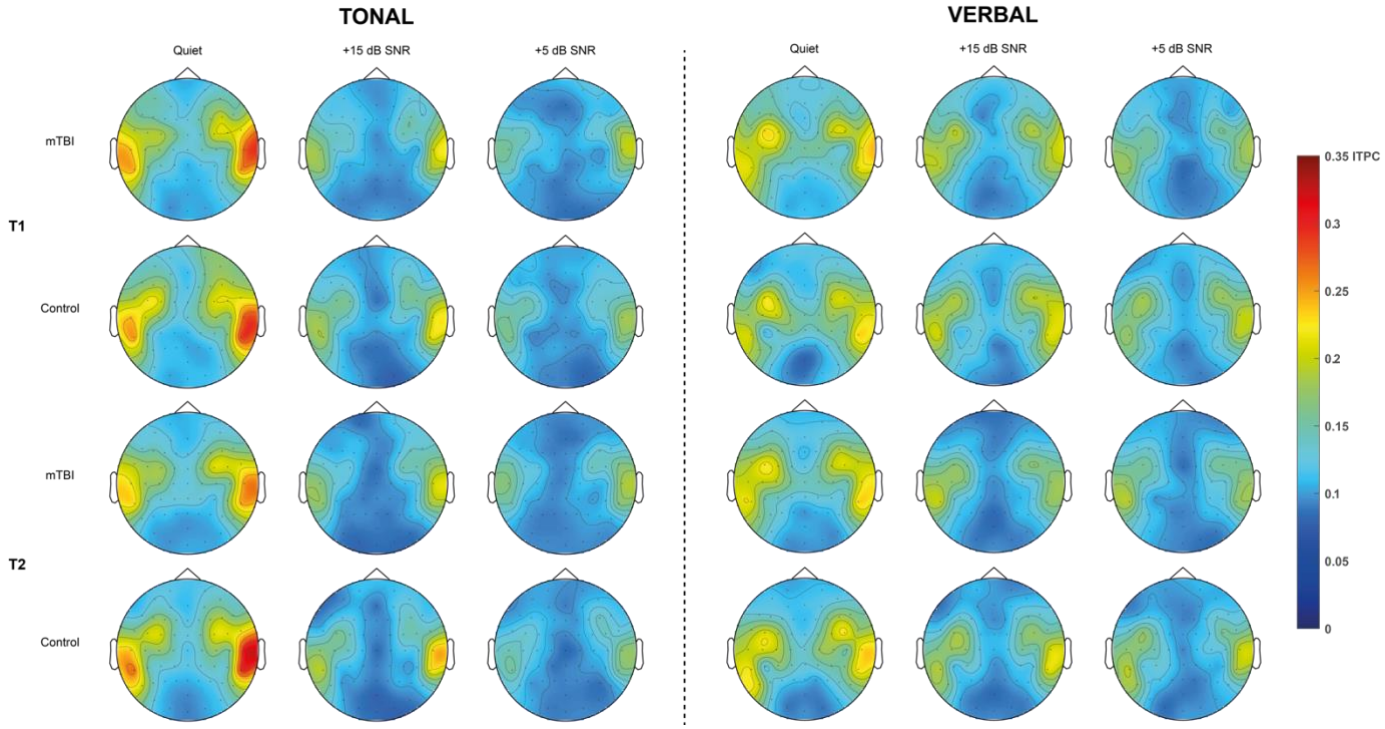

Figure 2. Topoplots of phase synchronization ITPC values in the mTBI and control groups for frequencies 4 to 60 Hz between 100-400 msec.

Table 3. Mixed factorial ANOVA results for ta- and bg- frequency ranges ITPC analysis values.

ITPC	ta-ITPC frequency range					Bg-ITPC frequency range				
	df (between groups)	df (within groups)	F	p≤	η2	df (between groups)	df (within groups)	F	p≤	η2
Time (T)	1	19	0.726	0.405	0.037	1	19	0.678	0.42	0.034
Stimulus (S)	1	19	1.229	0.281	0.061	1	19	2.281	0.147	0.107
Listening Condition (LC)	1.267	24.078	37.086	**<.001**	0.661	1.293	24.575	67.973	**<.001**	0.782
Electrode (E)	1.897	36.045	33.403	**<.001**	0.637	1.389	26.396	54.652	**<.001**	0.742
Group (G)	1	19	4.107	0.057	0.178	1	19	0.404	0.532	0.021
T × G	1	19	1.309	0.267	0.064	1	19	0.022	0.884	0.001
S × G	1	19	3.441	0.079	0.153	1	19	0.175	0.68	0.009
LC × G	2	38	1.539	0.228	0.075	2	38	0.832	0.443	0.042
E × G	2	38	0.769	0.47	0.039	2	0.007	0.719	0.494	0.036
T × S	1	19	0.115	0.738	0.006	1	19	0.307	0.586	0.016
T × S × G	1	19	3.235	0.088	0.145	1	19	0	0.987	0
T × LC	2	38	0.513	0.603	0.026	2	38	1.585	0.218	0.077
T × LC × G	2	38	1.467	0.243	0.072	2	38	1.293	0.286	0.064
S × LC	2	38	0.56	0.576	0.029	1.363	25.892	14.689	**<.001**	0.436
S × LC × G	2	38	0.55	0.582	0.028	2	38	2.325	0.112	0.109
T × S × LC	2	38	1.657	0.204	0.08	2	38	1.171	0.321	0.058
T × S × LC × G	2	38	1.618	0.212	0.078	2	38	0.185	0.831	0.01
T × E	2	38	1.642	0.207	0.08	2	38	0.985	0.383	0.049
T × E × G	2	38	0.435	0.651	0.022	2	38	1.445	0.248	0.071
S × E	2	38	1.715	0.194	0.083	1.964	37.307	7.845	**0.002**	0.292
S × E × G	2	38	0.901	0.415	0.045	2	38	0.109	0.897	0.006
T × S × E	2	38	0.483	0.621	0.025	2	38	0.574	0.568	0.029
T × S × E × G	2	38	0.375	0.69	0.019	2	38	0.677	0.514	0.034
LC × E	4	76	2.081	0.092	0.099	2.669	50.708	5.168	**0.005**	0.214
LC × E × G	4	76	0.183	0.946	0.01	4	76	0.285	0.887	0.015
T × LC × E	4	76	0.933	0.45	0.047	4	76	1.071	0.377	0.053
T × LC × E × G	4	76	0.928	0.452	0.047	4	76	0.938	0.447	0.047
S × LC × E	2.913	55.355	4.842	**0.005**	0.203	3.101	58.926	12.83	**<.001**	0.403
S × LC × E × G	4	76	1.542	0.199	0.075	4	76	1.969	0.108	0.094
T × S × LC × E	4	76	0.542	0.705	0.028	4	76	1.314	0.272	0.065
T × S × LC × E × G	4	76	0.266	0.899	0.014	4	76	0.779	0.543	0.039

For the ta-ITPC and bg-ITPC oscillatory activities, the 5-factor interaction was not significant [ta-ITPC: $F(4,76) = .266$, $p = .899$, $\eta^2 = .014$; bg-ITPC: $F(4,76) = .779$, $p = .543$, $\eta^2 = .039$]. For these measures, the Group factor was not significant [ta-ITPC: $F(1,19) = 4.107$, $p = .057$, $\eta^2 = .178$; bg-ITPC: $F(1,19) = .404$, $p = .532$, $\eta^2 = .021$]. However, for

the two frequency categories, the largest significant interaction was a three-factor interaction Stimulus × Listening Condition × Electrode [ta-ITPC: $F(2.913,55.355) = 4.842$, $p = .005$, $\eta^2 = .203$; bg-ITPC: $F(3.101,58.926) = 12.830$, $p < .001$, $\eta^2 = .403$]. Further analysis of the Listening Condition × Electrode interaction was conducted under the Stimulus factor and summarized below.

3.2.1. Theta and Alpha frequency range ITPC analysis

3.2.1.1. Tonal stimulus

Pairwise comparisons were completed for the Electrode factor. Results showed that for the right and left electrodes, all conditions were significantly different from each other, with the quiet condition having the largest ITPC values, then in noise at +15 dB SNR and the +5 dB SNR [C5, all conditions: $t > 2.725$, $p_{bonferroni} < .017$, $d > .594$; C6, all conditions: $t > 2.688$, $p_{bonferroni} < .017$, $d > .586$]. ta-ITPC synchronization values in the central electrode were larger in the quiet condition than both levels of noise [Quiet vs. +15 and +5: $t > 3.479$, $p_{bonferroni} < .017$, $d > .758$; +15 vs. +5 : $t = 0.629$, *ns*].

3.2.1.2. Verbal stimulus

Pairwise comparisons were conducted for the Electrode factor. For the left electrode, the ITPC activity was significantly smaller in noise at +5 dB SNR than in the two other listening conditions [+5 vs. Quiet and +15: $t > 3.110$, $p_{bonferroni} < .017$, $d > .678$; Quiet vs. +15: $t = 1.527$, *ns*]. For both the central and right electrodes, the ta-ITPC values were significantly greater in the quiet condition than in both noise conditions [Cz: Quiet vs. +15 and +5: $t > 5.215$, $p_{bonferroni} < .017$, $d > 1.240$; +15 vs. +5 : $t = 0.135$, *ns*; C6: Quiet vs. +15 and +5: $t > 2.728$, $p_{bonferroni} < .017$, $d > .594$; +15 vs. +5 : $t = 0.764$, *ns*].

3.2.2. Beta and Gamma frequency range ITPC analysis

3.2.2.1. Tonal stimulus

The Listening x Electrode interaction was significant and decomposed by isolating the Electrode factor. For both the right and left electrodes showed that the largest bg-ITPC values were elicited in the most favourable listening conditions [C5, all conditions: $t >$

2.918, $p_{bonferroni} < .017$, $d > .636$; C6, all conditions: $t > 4.477$, $p_{bonferroni} < .017$, $d > .976$]. For the central electrode, the bg-ITPC values were smaller in both noise listening conditions than the quiet condition [Quiet vs. +15 and +5 dB SNR: $t > 4.078$, $p_{bonferroni} < .017$, $d > .889$; 15 vs. +5: $t = 0.045$, *ns*].

3.2.2.2. Verbal stimulus

Only the main effects of the Listening Condition [$F(2,40) = 19.556$, $p < .001$, $\eta^2 = .494$] and Electrode [$F(2,40) = 25.715$, $p < .001$, $\eta^2 = .563$] factors were significant. bg-ITPC values were greater in the quiet listening condition than in both noise conditions [Quiet vs. +15 and +5 dB SNR: $t > 4.345$, $p_{bonferroni} < .017$, $d > .947$; 15 vs. +5: $t = 2.234$, *ns*]. The central electrode yielded smaller ITPC values than the left and right electrodes [Cz vs. C5 and C6: $t > 4.539$, $p_{bonferroni} < .017$, $d > .990$; C5 vs C6: $t = 2.445$, *ns*].

4. Discussion

The present study investigated the impacts of mTBI on children's auditory functions with two types of measures: ALRs and cortical oscillations with phase synchronization. Children's AEPs were measured twice due to previous mTBI literature showing that spontaneous recovery is expected within one month following mTBI. However, post mTBI effects can persist or worsen over time for a subset of children (Zemek et al., 2016). The current results showed very few differences between children with and without mTBI. The differences were found only for N2 latency at the electrode located on the right hemisphere and at the central electrode, which was shorter in the group with mTBI than in the control group These findings defy expectations and are not supported by the literature (Vander Werff & Rieger, 2019b). They do not appear to be related to an impact of mTBI on auditory function. However, the small sample size and high variability of the results may influence the findings and thus limit their interpretation.

No differences between groups or time measures were recorded in ITPC values. While ITPC values reduction was found in other populations, such as children with autism (Yu et al., 2018) or children with language disorders (Campos et al., 2023), the present study failed to find such reductions when comparing mTBI children to controls. For ARLs and

ITPC measures, when differences between electrodes were observed, right and left electrodes generally had shorter latencies, greater amplitudes and greater ITPC values compared to the central electrode. This aligns with the literature regarding maturation as central-evoked potentials generally mature later in life (Bishop et al., 2011; Müller et al., 2009).

There were no significant differences between groups regarding the effects of listening conditions and type of stimulus on ALR or ITPC values. However, the effects of the listening condition were consistent with the literature, as the quiet condition yielded the largest amplitude and ITPC values and the shortest latencies, independently of the groups (Benítez-Barrera et al., 2021; Duquette-Laplante et al., 2024; Gustafson et al., 2019; Koerner & Zhang, 2015). In noise, +15 and +5 dB SNR had a significant disruptive effect on the ALR amplitude, latency and ITPC values, with +5 dB SNR having the greatest effect. The lack of differences in noise-specific conditions differs from previous studies conducted with children with learning disabilities (LD) (Cunningham et al., 2001; Hayes et al., 2003) and adults with mTBI (Vander Werff & Rieger, 2019b). These studies found greater reductions of amplitudes and elongated latencies in noise conditions for LD children when compared to typically developing controls (Cunningham et al., 2001; Hayes et al., 2003) or for mTBI adults compared to controls (Vander Werff & Rieger, 2019b). However, the current study could not find such an effect.

Differences between T1 and T2 were only observed with the ALRs: larger P1 and N2 amplitudes and shorter N2 latency at the first measuring time. The maturation changes hypothesis could partially explain the differences between time measures (Ponton et al., 2000; Wunderlich et al., 2006). However, as three months is a short time window and small groups can increase intersubject variability, these differences could be spurious.

The lack of differences between groups in the current study does not necessarily indicate that mTBI does not impact ALRs or phase synchronization. Several factors could partially explain the absence of difference between groups, such as the great heterogeneity among the participants and the small sample size. Synaptic pruning and abrupt neuronal changes

elicit great intrasubject variability, which could have diminished the significant differences between groups (Devous et al., 2006; Paus et al., 1999).

5. Limitations and Future Directions

ALR wave peak components identification in noise was difficult, as indicated by the 79% inter-judge score. In order to increase the visibility of the components in noise, the improvement of SNR could be attained by increasing the number of trials per condition. While the number of presentations per block per condition was 200, the minimum recommended (Luck, 2014) was increased trials for children, which could effectively increase wave component visibility. However, increasing the number of trials would increase the duration of the experiment, which in turn could increase fatigue. It would be useful to find an optimal compromise between the number of trials and the duration of the experiment. Another limitation is related to the sex compositions. The present study had limited female participants, hindering the exploration of sex-based differences in noise's impact on listening abilities. Future studies with a bigger sample size should investigate sex differences. Future research should also investigate children with multiple mTBIs. It is possible that the neural legacy of a single concussion in children does not leave a permanent effect. Having had a mTBI increases the risk of having other mTBIs (Lasry et al., 2017).

6. Conclusions

The results of the current study represent the first step in evaluating AEPs in noise in children following an mTBI. Reported differences between groups were minimal. Parameter modulation of the noise stimulation was in line with the literature (Duquette-Laplante et al., 2024; Gustafson et al., 2019; Maamor & Billings, 2017). Smaller SNRs were more disruptive, and the tonal stimulus elicited smaller and shorter values. Such results could lead to an understanding of how further analysis of ITPC and ALR values could help in the rehabilitation and treatment of auditory processing difficulties. As these difficulties are often more apparent in challenging listening environments such as noise, the use of AEPs evoked in noise could help monitor the potential benefits of therapy or rehabilitation in those listening situations.

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8. Data availability statement

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

9. Authors contributions

Fauve Duquette-Laplante: Conceptualization; Data curation; Formal Analysis; Funding Acquisition; Investigation; Methodology; Project administration; Software; Supervision; Validation; Visualization; Writing - Original Draft Preparation; Writing – review and editing. **Benoît Jutras**: Conceptualization; Formal Analysis; Funding Acquisition; Methodology; Project Administration; Resources; Supervision; Validation; Writing - Original Draft Preparation; Writing – review and editing. **Amineh Koravand**: Conceptualization; Formal Analysis; Funding Acquisition; Methodology; Project administration; Resources; Supervision; Writing - Original Draft Preparation; Writing – review and editing.

The following people will potentially be added to the author list: Marianne Dubuc, Boutheina Jemel, Jocelyn Gravel, Miriam Beauchamp, Justine Ratelle and Isabelle Gagnon.

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Supplemental Materials

Table 4. Mean values, standard errors for P1 and N2 amplitude values for stimuli, listening conditions, and electrodes in mTBI and control groups.

Peak Amplitude			P1						N2					
			Quiet		+15 dB SNR		+5 dB SNR		Quiet		+15 dB SNR		+5 dB SNR	
			T1	T2	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2
mTBI	Tonal	C5	8.552 (2.440)	10.185 (2.527)	6.341 (1.738)	8.200 (2.655)	9.740 (1.376)	7.918 (1.876)	-19.170 (3.717)	-17.256 (1.943)	-8.748 (2.610)	-11.823 (3.101)	-5.985 (2.049)	-6.322 (2.472)
		Cz	2.263 (1.908)	7.517 (2.598)	1.433 (2.296)	2.711 (1.997)	0.754 (1.168)	5.440 (1.827)	-5.126 (2.808)	-2.099 (2.378)	-9.032 (3.054)	-2.813 (2.258)	-1.796 (1.746)	-2.525 (1.555)
		C6	11.588 (2.211)	9.208 (1.928)	8.688 (2.348)	7.185 (1.980)	9.216 (1.671)	5.428 (1.651)	-21.409 (3.622)	-14.691 (1.179)	-8.425 (2.539)	-11.507 (2.584)	-6.195 (2.565)	-7.262 (1.537)
	Verbal	C5	5.519 (3.901)	16.009 (2.645)	9.359 (2.984)	13.915 (2.809)	8.799 (3.348)	13.607 (2.727)	-25.529 (3.834)	-21.329 (2.787)	-8.376 (2.764)	-12.652 (2.309)	-9.101 (3.214)	-10.448 (2.889)
		Cz	1.342 (2.504)	3.924 (1.961)	4.343 (1.802)	1.786 (1.720)	-0.654 (2.721)	3.375 (1.493)	-11.164 (4.251)	-4.463 (1.577)	-11.158 (2.646)	-8.355 (1.672)	-9.577 (2.708)	-6.316 (2.534)
		C6	7.235 (2.639)	7.243 (2.505)	10.642 (2.856)	6.986 (2.438)	13.098 (2.851)	4.648 (2.047)	-15.597 (3.466)	-12.346 (3.637)	-13.942 (4.496)	-9.454 (3.815)	-9.524 (3.886)	-13.783 (4.548)
Control	Tonal	C5	9.502 (2.452)	7.985 (1.757)	11.026 (2.890)	6.505 (1.708)	7.173 (2.230)	8.137 (1.124)	-28.277 (5.796)	-19.899 (4.857)	-11.908 (3.342)	-13.135 (4.499)	-12.695 (3.731)	-10.441 (2.888)
		Cz	8.087 (2.167)	3.664 (1.556)	-0.158 (2.491)	-0.027 (1.434)	3.151 (1.452)	1.853 (0.512)	-0.074 (2.893)	-2.356 (3.111)	-8.494 (3.034)	-7.815 (2.779)	-6.402 (2.573)	-1.202 (1.357)
		C6	7.028 (2.194)	6.640 (3.749)	7.694 (3.660)	5.435 (2.265)	8.094 (2.220)	6.478 (1.878)	-26.007 (6.156)	-18.897 (4.062)	-10.740 (3.914)	-11.877 (3.954)	-7.810 (3.173)	-10.534 (2.244)
	Verbal	C5	12.152 (2.668)	7.899 (3.633)	6.725 (4.091)	8.213 (3.129)	11.088 (4.042)	7.370 (2.609)	-23.245 (5.386)	-18.448 (5.845)	-19.302 (6.818)	-15.448 (5.322)	-13.415 (5.665)	-8.113 (4.360)
		Cz	5.523 (2.089)	5.174 (1.465)	1.285 (1.365)	-0.895 (1.365)	1.887 (1.740)	-0.833 (2.407)	-1.738 (3.506)	-5.099 (1.703)	-8.359 (2.725)	-7.844 (2.236)	-11.151 (2.258)	-14.635 (2.450)
		C6	10.763 (2.564)	3.713 (3.239)	8.328 (2.422)	8.046 (2.557)	5.874 (2.065)	7.541 (1.355)	-23.023 (8.163)	-24.840 (4.765)	-22.580 (7.755)	-16.977 (4.589)	-21.521 (6.578)	-10.477 (2.583)

Table 5. Mean values, standard errors for P1 and N2 latency values for stimuli, listening conditions, and electrodes in mTBI and control groups.

Peak Latency			P1						N2					
			Quiet		+15 dB SNR		+5 dB SNR		Quiet		+15 dB SNR		+5 dB SNR	
			T1	T2	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2
mTBI	Tonal	C5	96.000 (3.894)	94.182 (4.651)	97.636 (4.505)	110.091 (3.644)	112.100 (6.362)	121.091 (4.331)	206.636 (7.948)	207.455 (7.801)	216.273 (5.896)	214.545 (3.304)	229.500 (7.684)	219.000 (4.620)
		Cz	84.778 (5.325)	86.800 (4.746)	103.500 (6.978)	106.667 (5.641)	116.375 (8.488)	129.667 (8.175)	277.111 (11.592)	277.300 (9.222)	281.250 (11.702)	292.667 (9.873)	304.875 (12.098)	314.444 (8.548)
		C6	100.182 (6.929)	98.455 (3.721)	121.909 (7.481)	112.400 (6.292)	129.000 (6.378)	112.125 (4.347)	216.375 (9.244)	210.636 (10.202)	223.333 (9.659)	208.200 (6.728)	231.444 (10.865)	222.125 (7.657)
	Verbal	C5	86.818 (6.967)	116.818 (7.044)	104.455 (6.714)	128.182 (6.160)	110.545 (5.030)	143.636 (8.031)	230.091 (9.626)	252.636 (9.135)	231.545 (7.446)	257.364 (11.535)	234.273 (6.267)	266.091 (12.475)
		Cz	89.100 (2.968)	97.091 (5.475)	112.800 (6.987)	124.273 (8.653)	113.875 (5.413)	123.750 (4.186)	286.500 (14.545)	291.091 (8.061)	307.800 (11.554)	311.273 (4.862)	329.000 (10.409)	320.500 (5.939)
		C6	91.727 (7.306)	92.545 (4.995)	108.273 (5.948)	104.000 (7.469)	110.444 (6.231)	116.000 (6.995)	224.818 (11.018)	198.455 (8.164)	231.545 (12.003)	213.727 (5.587)	260.667 (15.960)	229.500 (6.502)
Control	Tonal	C5	91.200 (4.835)	95.900 (2.726)	103.000 (4.695)	102.400 (4.392)	104.889 (3.424)	113.400 (3.380)	208.400 (10.735)	210.600 (8.374)	223.400 (14.598)	219.200 (9.239)	225.700 (10.894)	232.700 (6.891)
		Cz	100.333 (6.121)	90.700 (5.714)	138.857 (12.386)	105.500 (9.999)	140.500 (11.257)	123.857 (9.489)	322.444 (8.751)	276.800 (8.197)	321.778 (9.227)	299.200 (11.099)	333.750 (6.762)	291.143 (4.416)
		C6	94.500 (8.010)	95.600 (7.842)	101.700 (9.692)	107.778 (9.912)	112.300 (8.548)	125.125 (5.309)	223.400 (14.221)	234.200 (9.506)	239.000 (14.608)	235.889 (5.246)	252.200 (18.498)	239.375 (5.211)
	Verbal	C5	99.300 (7.140)	94.500 (10.812)	110.900 (11.337)	108.900 (9.172)	117.800 (9.469)	107.875 (14.776)	251.000 (9.634)	266.400 (15.242)	273.700 (12.169)	276.300 (14.524)	283.800 (12.764)	292.750 (15.165)
		Cz	95.700 (6.815)	95.700 (5.631)	108.556 (10.159)	115.333 (7.186)	125.778 (8.048)	105.750 (3.872)	319.300 (6.857)	302.200 (10.609)	332.333 (7.458)	308.600 (12.630)	344.556 (6.474)	325.143 (6.534)
		C6	107.100 (7.255)	95.900 (8.329)	122.600 (7.795)	116.100 (9.555)	135.222 (6.995)	141.375 (11.324)	275.100 (13.609)	271.100 (11.952)	288.900 (15.880)	299.800 (14.070)	313.444 (17.078)	324.875 (11.144)

Table 6. Mean values, standard errors for ta- and bg- ITPC values for stimuli, listening conditions, and electrodes in mTBI and control groups.

Phase synchronization (ITPC)			ta-ITPC frequency range						bg-ITPC frequency range					
			Quiet		+15 dB SNR		+5 dB SNR		Quiet		+15 dB SNR		+5 dB SNR	
			T1	T2	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2
mTBI	Tonal	C5	0.228 (0.027)	0.174 (0.025)	0.132 (0.021)	0.132 (0.015)	0.119 (0.018)	0.133 (0.009)	0.172 (0.012)	0.178 (0.010)	0.133 (0.010)	0.135 (0.009)	0.130 (0.011)	0.130 (0.008)
		Cz	0.155 (0.032)	0.129 (0.016)	0.101 (0.014)	0.088 (0.011)	0.096 (0.015)	0.090 (0.010)	0.124 (0.012)	0.124 (0.011)	0.098 (0.006)	0.091 (0.007)	0.102 (0.005)	0.097 (0.005)
		C6	0.190 (0.028)	0.158 (0.024)	0.106 (0.014)	0.121 (0.013)	0.097 (0.010)	0.107 (0.012)	0.154 (0.016)	0.159 (0.011)	0.106 (0.008)	0.127 (0.008)	0.113 (0.010)	0.119 (0.009)
	Verbal	C5	0.336 (0.037)	0.296 (0.036)	0.210 (0.041)	0.203 (0.023)	0.166 (0.026)	0.185 (0.026)	0.176 (0.013)	0.177 (0.011)	0.165 (0.009)	0.166 (0.015)	0.152 (0.013)	0.138 (0.011)
		Cz	0.243 (0.052)	0.184 (0.027)	0.126 (0.042)	0.090 (0.007)	0.139 (0.029)	0.104 (0.018)	0.140 (0.012)	0.136 (0.013)	0.114 (0.015)	0.097 (0.007)	0.108 (0.008)	0.101 (0.006)
		C6	0.197 (0.031)	0.230 (0.022)	0.177 (0.022)	0.167 (0.019)	0.156 (0.027)	0.162 (0.021)	0.124 (0.010)	0.135 (0.008)	0.139 (0.012)	0.121 (0.008)	0.121 (0.016)	0.124 (0.007)
Control	Tonal	C5	0.242 (0.050)	0.215 (0.038)	0.168 (0.033)	0.177 (0.025)	0.153 (0.039)	0.142 (0.020)	0.196 (0.018)	0.164 (0.011)	0.149 (0.012)	0.148 (0.016)	0.137 (0.016)	0.132 (0.012)
		Cz	0.159 (0.025)	0.112 (0.014)	0.092 (0.012)	0.076 (0.008)	0.112 (0.010)	0.079 (0.008)	0.130 (0.006)	0.117 (0.007)	0.108 (0.004)	0.088 (0.005)	0.101 (0.003)	0.084 (0.004)
		C6	0.214 (0.039)	0.170 (0.032)	0.137 (0.028)	0.149 (0.029)	0.153 (0.027)	0.112 (0.021)	0.168 (0.014)	0.161 (0.011)	0.118 (0.014)	0.124 (0.010)	0.130 (0.011)	0.124 (0.012)
	Verbal	C5	0.286 (0.045)	0.323 (0.033)	0.233 (0.051)	0.240 (0.032)	0.215 (0.048)	0.208 (0.031)	0.175 (0.014)	0.189 (0.012)	0.163 (0.021)	0.165 (0.017)	0.164 (0.024)	0.158 (0.015)
		Cz	0.172 (0.016)	0.153 (0.016)	0.120 (0.018)	0.102 (0.012)	0.105 (0.017)	0.092 (0.009)	0.143 (0.010)	0.130 (0.015)	0.114 (0.010)	0.109 (0.006)	0.106 (0.009)	0.094 (0.008)
		C6	0.244 (0.059)	0.211 (0.046)	0.213 (0.050)	0.212 (0.044)	0.208 (0.047)	0.157 (0.043)	0.155 (0.014)	0.143 (0.013)	0.143 (0.016)	0.135 (0.018)	0.128 (0.016)	0.125 (0.018)

Table 7. ANOVA and t-tests results for P1 and N2 amplitude values.

P1 amplitude	Tonal					Verbal				
	df (between groups)	df (within groups)	F	p≤	η2	df (between groups)	df (within groups)	F	p≤	η²
Time (T)	1	19	0.245	0.626	0.013	1	19	0.069	0.796	0.004
Listening Condition (LC)	2	38	4.484	0.018	0.191	2	38	0.683	0.511	0.035
Group (G)	1	19	0.594	0.45	0.03	1	19	0.524	0.478	0.027
Electrode (E)	2	38	19.915	<.001	0.512	2	38	1.481	<.001	0.356
T × G	1	19	1.055	0.317	0.053	1	19	1.874	0.187	0.090
LC × G	2	38	0.052	0.95	0.003	2	38	2.212	0.123	0.104
E × G	2	38	0.369	0.694	0.019	2	38	0.161	0.852	0.008
T × LC	2	38	0.059	0.942	0.003	2	38	0.264	0.769	0.014
T × LC × G	2	38	0.580	0.565	0.03	2	38	5.271	0.01	0.217
T × E	1.481	28.131	0.590	0.512	0.03	1.534	29.14	3.847	0.043	0.168
LC × E	4	76	1787	0.14	0.086	4	76	1.387	0.246	0.068
G × LC × E	4	76	1925	0.115	0.092	4	76	0.551	0.699	0.028
T × LC × E	4	76	0.286	0.886	0.015	4	76	0.956	0.437	0.048
T × LC × E × G	4	76	2.079	0.092	0.099	4	76	2.620	0.041	0.121

	C5	Cz	C6	
Time (T)	$F = 1.333, p = .263, \eta^2 = .066$	$F = .022, p = .883, \eta^2 = .001$	$F = 3.937, p = .062, \eta^2 = .172$	
Listening Condition (LC)	$F = .257, p = .775, \eta^2 = .013$	$F = 2.559, p = .091, \eta^2 = .119$	$F = .408, p = .668, \eta^2 = .021$	
Group (G)	$F = .391, p = .539, \eta^2 = .020$	$F = .076, p = .786, \eta^2 = .004$	$F = .152, p = .701, \eta^2 = .008$	
T × G	$F = 5.172, p = .035, \eta^2 = .214$	$F = 1.361, p = .258, \eta^2 = .067$	$F = .516, p = .481, \eta^2 = .026$	
LC × G	$F = .986, p = .383, \eta^2 = .049$	$F = 2.000, p = .149, \eta^2 = .095$	$F = .316, p = .731, \eta^2 = .016$	
T × LC	$F = .732, p = .487, \eta^2 = .037$	$F = 1.327, p = .277, \eta^2 = .065$	$F = .234, p = .793, \eta^2 = .012$	
T × LC × G	$F = 2.937, p = .065, \eta^2 = .134$	$F = 1.177, p = .319, \eta^2 = .058$	$F = 5.899, p = .006, \eta^2 = .237$	
		C6 - Quiet condition	C6 - +15 dB SNR condition	C6 - +5 dB SNR condition
Time (T)		$F = 1.691, p = .209, \eta^2 = .082$	$F = 1.209, p = .285, \eta^2 = .06$	$F = 4.630, p = .044, \eta^2 = .196$
Group (G)		$F = 0, p = 1, \eta^2 = 0$	$F = .039, p = .846, \eta^2 = .002$	$F = .662, p = .426, \eta^2 = .034$
T × G		$F = 1.698, p = .208, \eta^2 = .082$	$F = .887, p = .358, \eta^2 = .045$	$F = 1.296, p = .005, \eta^2 = .351$
Independant sample T-Tests				
T1				$t = 2.016, p = .058, d = .881$
T2				$t = 1.153, p = .263, d = .504$

Table 7 (continued). ANOVA and t-tests results for P1 and N2 amplitude values.

	Tonal					Verbal				
N2 amplitude	df (between groups)	df (within groups)	F	p≤	η2	df (between groups)	df (within groups)	F	p≤	η^2
Time (T)	1	19	1.415	0.249	0.069	1	19	1815	0.194	0.087
Listening Condition (LC)	2	38	0.123	0.885	0.006	2	38	7.783	0.001	0.291
Group (G)	1	19	1.846	0.19	0.089	1	19	0.784	0.387	0.040
Electrode (E)	1.451	27.573	18.273	<.001	0.49	1.548	29.413	5.049	0.019	0.210
T × G	1	19	0.094	0.763	0.005	1	19	0.076	0.786	0.004
LC × G	2	38	0.123	0.885	0.006	2	38	1.142	0.254	0.070
E × G	2	38	0.647	0.529	0.033	2	38	1.099	0.344	0.055
T × LC	2	38	3.713	0.034	0.163	2	38	0.045	0.956	0.002
T × LC × G	2	38	0.346	0.71	0.018	2	38	3.702	0.034	0.163
T × E	2	38	0.063	0.939	0.003	2	38	0.174	0.841	0.009
LC × E	4	76	14.794	<.001	0.438	4	76	11.865	<.001	0.384
G × LC × E	4	76	1.032	0.396	0.052	4	76	3.591	0.01	0.159
T × LC × E	3.071	58.341	2.786	0.047	0.128	4	76	1.314	0.272	0.065
T × LC × E × G	4	76	1262	0.292	0.062	4	76	1.819	0.134	0.087

	(1) Time × Listening Condition × Electrode			(1) Listening Condition × Electrode × Group		
	C5	Cz	C6	C5	Cz	C6
Time (T)	F = .317, p = .579, η^2 = .016	F = 1315, p = .265, η^2 = .062	F = .190, p = .668, η^2 = .009			
Listening Condition (LC)	F = 2.988, p <.001, η^2 = .512	F = 6.336, p = .004, η^2 = .241	F = 2.308, p <.001, η^2 = .504	F = 23.050, p = .001, η^2 = .548	F = 4.451, p = .018, η^2 = .190	F = 3.741, p = .033, η^2 = .165
Group (G)				F = .124, p = .729, η^2 = .006	F = .046, p = .832, η^2 = .002	F = 1.580, p = .224, η^2 = .077
T × G						
LC × G				F = 3.549, p = .039, η^2 = .157	F = 4.244, p = .022, η^2 = .183	F = 1.138, p = .331, η^2 = .057
T × LC	F = 3.012, p = .060, η^2 = .131	F = .459, p = .635, η^2 = .022	F = 6.424, p = .004, η^2 = .243			
Paired sample T-tests						
Quiet T1 and Quiet T2			t = 2.188, p = .041, d = .477			
+15 T1 and +15 T2			t = .727, p = .476, d = .159			
+5 T1 and +5 T2			t = .907, p = .375, d = .198			
Independant sample T-Tests						
Quiet				t = .440, p = .667, d = .198	t = 1.563, p = .135, d = .683	
+15 dB SNR				t = 1.150, p = .274, d = .522	t = .736, p = .471, d = .322	
+5 dB SNR				t = .210, p = .836, d = .092	t = 1.910, p = .071, d = .834	

	(2) Listening Condition × Time × Group		
	Quiet condition	+15 dB SNR condition	+5 dB SNR condition
T1	t = .339, p = .738, d = .148	t = 1.096, p = .287, d = .479	t = 1.307, p = .207, d = .571
T2	t = .969, p = .345, d = .423	t = .961, p = .349, d = .42	t = .315, p = .756, d = .138

Table 8. ANOVA and t-tests results for P1 and N2 latency values.

P1 latency	Tonal					Verbal				
	df (between groups)	df (within groups)	F	p≤	η^2	df (between groups)	df (within groups)	F	p≤	η^2
Time (T)	1	20	0.051	0.824	0.003	1	20	1.147	0.297	0.054
Listening Condition (LC)	2	40	156.408	<.001	0.887	2	40	92.084	<.001	0.822
Electrode (E)	1.45	29.008	1.686	0.206	0.078	2	40	0.128	0.88	0.006
T × LC	2	40	1.083	0.348	0.051	2	40	0.025	0.976	0.001
T × E	2	40	0.828	0.444	0.04	2	40	2.025	0.145	0.092
LC × E	4	80	6.288	<.001	0.239	4	80	1.399	0.242	0.065
T × LC × E	4	80	1.174	0.329	0.055	4	80	1.735	0.151	0.080
Paired sample T-tests										
	C5		Cz		C6					
+10 and + 5 dB SNR	t= 3.844, p = .001, d = .839		t= 3.745, p = .001, d = .817		t= 3.348, p = .003, d = .731					
+10 and 0 dB SNR	t= 4.972, p <.001, d = 1085		t= 7.274, p <.001, d = 1.587		t= 5.04, p <.001, d = 1.1					
+5 and 0 dB SNR	t= 8.301, p <.001, d = 1.811		t= 12.53, p <.001, d = 2.734		t= 8.949, p <.001, d = 1.953					

N2 latency

(1)Time X Stimulus X Listening Condition X Electrode

	Tonal					Verbal				
	df (between groups)	df (within groups)	F	p≤	η^2	df (between groups)	df (within groups)	F	p≤	η^2
Time (T)	1	20	2.425	0.135	0.108	1	20	0.012	0.913	0.001
Listening Condition (LC)	2	40	41.055	<.001	0.672	1.515	3.305	55.516	<.001	0.735
Electrode (E)	2	40	74.646	<.001	0.789	2	40	27.755	<.001	0.581
T × LC	2	40	0.436	0.649	0.021	2	40	0.056	0.946	0.003
T × E	2	40	0.953	0.394	0.045	1.559	31.174	3.156	0.068	0.136
LC × E	4	80	0.519	0.722	0.025	4	80	2.624	0.041	0.116
T × LC × E	4	80	2.407	0.056	0.107	4	80	1.098	0.363	0.052
Paired sample T-tests						C5		Cz		C6
+10 and + 5 dB SNR						t= 1.548, p = .137, d = .338		t= 3.390, p = .003, d = .74		t= 5.962, p <.001, d = 1.301
+10 and 0 dB SNR						t= 1.667, p = .111, d = .364		t= 3.549, p = .002, d = .774		t= 6.015, p <.001, d = 1.313
+5 and 0 dB SNR						t= 3.786, p = .001, d = .826		t= 5.513, p <.001, d = 1.203		t= -9.001, p <.001, d = 1.964
(2) Stimulus × Electrode × Group										
Electrode (E)	2	38	73.02	<.001	0.794	2	38	35.147	<.001	0.649
Group (G)	1	19	5.388	0.032	0.221	1	19	3.184	<.001	0.614
E × G	2	38	0.535	0.59	0.027	2	38	7.145	0.002	0.273
Independant sample t-test										
						df	t	p≤	*d*	
C5						19	2.229	0.038	0.974	
Cz						19	1.686	0.108	0.737	
C6						19	6.133	<.001	2.68	

(3) Time × Electrode × Group

	C5				Cz				C6			
	df	t	p≤	*d*	df	t	p≤	*d*	df	t	p≤	*d*
T1	19	1.937	0.068	0.847	19	2.682	0.015	1.172	19	2.387	0.028	1.043
T2	19	1.439	0.166	0.629	19	0.087	0.932	0.038	19	7.208	<.001	3.15

Table 9. ANOVA and t-tests results for ta- and bg- ITPC values

	Tonal					Verbal				
	df (between groups)	df (within groups)	F	p≤	η^2	df (between groups)	df (within groups)	F	p≤	η^2
Theta and Alpha frequency range										
(1) Stimulus × Listening Condition × Electrode										
Listening Condition (LC)	1.596	31.924	25.977	<.001	0.565	1.319	26.389	18.672	<.001	0.483
Electrode (E)	1.936	38.717	42.469	<.001	0.68	1.807	36.143	14.563	<.001	0.421
LC × E	2.601	52.014	3.754	0.021	0.158	2.78	55.597	2.834	0.05	0.124

Paired sample T-tests	C5	Cz	C6	C5	Cz	C6
Quiet and +15 dB SNR	t = 3.346, p=.003, d=.730	t = 3.480, p=.002, d=.759	t = 2.689, p=.014, d=.587	t = 1.527, p = .143, d=.333	t = 5.216, p <.001, d=.595	t = 2.729, p=.013, d=.595
Quiet and +5 dB SNR	t = 4.726, p<.001, d=1.031	t = 4.001, p <.001, d=.873	t = 5.155, p <.001, d=1.125	t = 3.111, p=.006, d=.679	t = 5.686,p <.001, d=.598	t = 2.738, p=.013, d=.598
+15 and +5 dB SNR	t = 2.726, p=.013, d=.595	t = .629, p=.537, d=.137	t = 3.770, p= .001, d=.823	t = 5.164, p <.001, d=1.127	t = .135, p=.894, d=.167	t = .764, p=.454, d=.167
Beta and Gamma frequency range						
(1) Stimulus × Listening Condition × Electrode						
Listening Condition (LC)	1.163	23.261	55.278	<.001	0.734	1.704	34.088	19.556	<.001	0.494
Electrode (E)	1.477	29.539	64.346	<.001	0.763	1.639	32.786	25.715	<.001	0.563
LC × E	2.594	51.885	13.646	<.001	0.406	4	80	1.227	0.306	0.058

Paired sample T-tests	C5	Cz	C6
+10 and +5 dB SNR	t = 5.417, p <.001, d=1.182	t = 4.497, p <.001, d=.981	t = 6.492, p <.001, d=1.417
+10 and 0 dB SNR	t = 6.255, p <.001, d = 1.365	t = 4.079, p <.001, d=.89	t = 8.456, p <.001, d=1.845
+5 and 0 dB SNR	t = 2.919, p=.008, d=.637	t = -.045, p=.965, d=.01	t = 4.478, p <.001, d=.977

CHAPTER 4. General Discussion

In recent years, post mild traumatic brain injury (mTBI) symptoms have been widely explored (Babcock et al., 2013; Babikian et al., 2015; Barlow et al., 2015; Lumba-Brown et al., 2018; Lyons et al., 2022; Zemek et al., 2016). Nevertheless, the extent of the impact of mTBI on children's central auditory system has yet to be thoroughly investigated. The current thesis project's general objective was to document the central auditory processing abilities/functions following mTBI in school-aged children with behavioural and electrophysiological measures and if these measures changed over time. To achieve this aim, a behavioural and an electrophysiological experiment were conducted with both children diagnosed with the first mTBI and age- and sex- matched controls (see Figure 4, Chapter 1. Introduction, p.17). All the measures for both experiments were conducted twice – T1, within 14 days of the injury (or days or weeks following recruitment for controls) and T2, at least three months following T1.

4.1. Behavioural experiment

This experiment was composed of six central auditory behavioural tests – *Test de mots dans le bruit* (TMB) (Lagacé et al., 2010), Masking level difference (MLD) (Lynn et al., 1981), Pitch Pattern Sequence test (PPST) (Musiek, 1994), Duration Pattern test (DPT) (Musiek, 1994), *Écoute dichotique de chiffres* (EDC) (Jutras et al., 2012) and Gaps in noise test (GIN) (Shinn et al., 2009), a neuropsychological screening test battery – the Central Nervous System Vital Signs (CNSVS) (Gualtieri & Johnson, 2006) and 3 French adapted questionnaires – Listening Inventories for Education UK Individual Hearing Profile (LIFE-UK) (Canning, 1999; Jutras et al,. 2017), Scale of Auditory Behaviours (SAB) (Gagnon et al., 2009; Schow & Seikel, 2007) and Post Concussion Symptom Inventory (PCSI) (Duquette-Laplante, 2020; Gioia et al., 2012). Results showed that temporal processing test scores were significantly lower, and the binaural interaction thresholds were significantly higher in children with a mTBI than in the control group. These results align with recent literature findings, as about 60% of children with moderate to severe TBI failed temporal processing tests (De Godoy et al., 2022). From a clinical perspective, these auditory difficulties could be named as acquired auditory processing disorder (APD) in some children with

mTBI. APD has been defined as a neural processing deficit of auditory information (American Speech-Language-Hearing Association – ASHA, 2005). Such auditory difficulties can impact the children's life. It is generally evaluated with a central auditory behavioural test battery, as the one used in the present study. Two criteria must be met in order to diagnose APD in the absence of peripheral hearing loss in Canada: (1) scores of at least two central auditory behavioural tests at least 2 standard deviations below the mean or score of one central auditory behavioural test at 3 standard deviations from the mean and significant functional difficulties (ASHA, 2012); (2) these results should be maintained over time (Canadian Interorganizational Steering Group for Speech-Language Pathology and Audiology, 2012). When using this perspective to review the individual results of the current study, only four (mTBI02, mTBI05, mTBI07, mTBI10) would meet the criteria for APD diagnosis. They all fail at least two tests more than two standard deviations from the mean in both measure times (see Table 1). Reviewing all failed tests individually, seven participants within 14 days of the injury and seven participants three months later had at least one abnormal score on any auditory behavioural tests. It was not necessarily the same participants who failed the tests at both measure times. When observing auditory behavioural test results patterns, participants could be separated into four categories: participants with persistent difficulties (at least one test failed at T1 and T2), participants with remediated difficulties (at least one test failed at T1 and no test failed at T2), participants with appearing difficulties (no test failed at T1 and at least one test failed at T2) and participants with no difficulties (no test failed at T1 and at T2).

Literature reports that between 70 and 90% of children show no difficulties or spontaneously recover within four weeks from mTBI (Babcock et al., 2013; Babikian et al., 2015; Zemek et al., 2016). In the current study, four participants (mTBI01, mTBI08, mTBI09, mTBI11) either never showed difficulties or spontaneously recovered as they had no difficulties when tested at least three months after the injury. This represents less than half of the reported recovery rate. When including the two participants (mTBI03, mTBI04) who did not meet APD diagnosis criteria three months after the injury, the recovery rate results increased to 54% of participants. Moreover, difficulties and symptoms or their absence in the acute stage of the injury do not necessarily predict the long-term impacts of the mTBI (Zemek et al., 2016). This can be seen in the current study in six participants. Changes in auditory test scores were recorded over time. When including the comparison with age-appropriate norms, three children had increasing (mTBI07) or appearing

difficulties (mTBI03, mTBI06), and four children (mTBI04, mTBI08, mTBI10, mTBI11) had total or partial remediation of their difficulties (see Table 1).

Table 1. Raw scores for auditory behavioural tests for the 11 participants with mTBI*.

Auditory Behavioural tests		**EDC**		**PPST**		**TMB**		**DPT**		**MLD**			**GIN**			
		RE	LE	RE	LE	RE	LE	RE	LE	SΦNΦ	SπNΦ	Diff	Th RE	Th LE	% RE	% LE
mTBI01	Time 1	100	88	93	100	66	60	47	70	61	50	11	5	6	62	70
	Time 2	100	93	83	100	71	80	70	60	64	47	17	6	5	65	73
mTBI02	Time 1	98	93	30	50	54	66	33	30	64	47	17	5	6	82	67
	Time 2	100	90	40	7	77	71	37	37	64	47	17	5	6	70	62
mTBI03	Time 1	93	95	43	43	63	66	40	47	68	49	19	4	4	73	75
	Time 2	95	95	43	60	60	66	57	57	65	50	15	5	5	73	77
mTBI04	Time 1	93	93	100	100	43	43	60	63	61	47	14	6	5	63	67
	Time 2	95	100	87	87	66	77	67	93	61	49	12	5	5	73	63
mTBI05	Time 1	93	93	56	56	69	63	43	60	62	48	14	4	5	77	72
	Time 2	90	93	73	60	77	74	67	70	59	47	12	4	5	78	73
mTBI06	Time 1	100	98	100	100	71	63	83	87	68	55	13	4	4	77	78
	Time 2	95	98	93	70	60	80	80	77	70	53	17	10	5	48	72
mTBI07	Time 1	80	80	0	17	66	69	17	20	59	46	13	6	8	62	48
	Time 2	65	80	30	27	49	57	33	20	63	50	13	10	10	48	55
mTBI08	Time 1	90	78	67	67	60	74	77	93	64	52	12	6	6	71	62
	Time 2	95	85	77	83	80	48	100	93	60	48	12	5	5	65	68
mTBI09	Time 1	98	95	93	93	51	54	60	53	63	46	17	4	4	73	73
	Time 2	95	95	100	100	48	66	83	73	56	48	8	3	3	77	80
mTBI10	Time 1	98	95	67	63	54	60	63	93	66	48	18	8	6	60	60
	Time 2	95	87	87	77	63	54	73	93	60	47	13	5	8	62	53
mTBI11	Time 1	98	93	37	33	71	57	43	23	66	52	14	5	5	67	67
	Time 2	95	98	93	83	69	57	93	77	62	49	13	4	5	80	73

* Scores in red are failing scores according to age-appropriate norms. Abbreviations: EDC: *Écoute Dichotique de chiffres* (Dichotic Digits test);PPST: Pitch Pattern Sequence Test; TMB: *Test de mots dans le bruit* (Word in noise test); DPT: Duration Pattern Test; MLD: Masking Level Difference; GIN: Gap in Noise; RE: Right Ear; LE: Left Ear; SΦNΦ: Threshold for signal in phase and Noise in phase; SπNΦ: Threshold for signal not in phase noise in phase; Diff: release of masking difference; ThRE: Threshold Right Ear; ThLE: Threshold Left Ear; %RE: Percentage score Right Ear; %LE: Percentage score Left Ear.

For both children whose scores declined over time (mTBI03 and mTBI06), different patterns emerge when looking at results from both the cognitive screening test (CNSVS) and the questionnaires (Life-UK, SAB and PCSI). Scores of mTBI03 on the cognitive screening test were abnormal at T1, but normal at T2 whereas mTBI06 has the opposite pattern with normal scores at T1, and abnormal at T2 (see Table 2).

Table 2. Standard scores for cognitive screening subscales for the 11 participants with mTBI*.

Cognitive Screening		NCI	Com Mem	Ver Mem	Vis Mem	Psych Speed	R T	Comp Atten	Cogn Flex	Process Speed	Exec Funct	Simp Atten	Motor Speed
mTBI01	Time 1	81	58	58	73	108	94	78	67	88	68	97	120
	Time 2	102	97	116	83	120	91	102	99	101	102	100	124
mTBI02	Time 1	97	101	99	102	98	92	99	94	89	94	105	106
	Time 2	95	96	103	91	99	98	91	91	100	92	83	99
mTBI03	Time 1	87	84	62	110	102	77	93	79	107	79	106	99
	Time 2	106	119	128	107	103	114	97	95	106	101	100	100
mTBI04	Time 1	102	118	112	116	93	100	95	104	99	107	55	90
	Time 2	102	105	93	113	90	102	96	117	100	119	33	84
mTBI05	Time 1	76	86	86	91	90	11	98	96	90	94	62	93
	Time 2	94	99	106	94	96	62	101	110	98	110	62	97
mTBI06	Time 1	111	111	120	100	116	114	107	106	110	107	97	117
	Time 2	90	79	86	80	87	91	98	97	77	100	97	95
mTBI07	Time 1	101	102	97	107	88	112	97	107	95	110	87	84
	Time 2	105	102	105	100	96	110	104	113	109	115	84	89
mTBI08	Time 1	103	117	105	123	136	108	73	81	109	83	106	144
	Time 2	124	119	120	113	143	135	112	112	130	116	113	142
mTBI09	Time 1	106	95	81	110	104	112	110	111	104	110	97	101
	Time 2	116	111	101	117	113	112	122	120	116	122	113	108
mTBI10	Time 1	110	98	116	83	128	127	99	96	134	98	105	119
	Time 2	116	114	103	118	119	128	108	112	118	115	105	115
mTBI11	Time 1	83	75	70	88	92	64	94	89	79	90	76	104
	Time 2	89	64	63	77	103	92	94	90	92	92	83	112

* Scores in yellow are Low Average and represent slight deficit; Score in orange are Low represent moderate deficit; Scores in red are Very Low and represent significant deficit. Abbreviations are: NCI: Neurocognitive Index; Com Mem: Composite Memory;Verb Mem: Verbal Memory;Vis Mem: Visual Memory; Psych Speed: Psychomotor Speed;RT: Reaction Time;Comp Atten: Complex Attention;Cogn Flex: Cognitive Flexibility;Process Speed: Processing Speed;Exec Funct: Executive Functioning; Simp Atten: Simple Attention.

For the questionnaires (see Table 3), mTBI03 reported an improvement in their own listening behaviours as their score for the LIFE-UK increased from T1to T2 whereas the parent reported a decrease in performance in their listening behaviours from T1 to T2. In the PCSI, both parent and child reported a decrease of symptoms between T1 and T2. However, the child indicated that symptoms had returned to pre-injury levels at T2 while the parent reported that not all symptoms had resolved (see Table 3). For mTBI06, the child perceived and the parent perceived similar listening behaviours from T1 to T2 (see Table 3). For the PCSI, both the parent and the child indicate the presence of symptoms post mTBI at T1 and T2 with no return to pre-injury. Finally, as only two children had increasing or appearing difficulties, definitive interpretation or analysis could not be done. However, for both children, the results from the PCSI indicated that post-mTBI symptoms were still present at T2. These results indicate the need for further investigation of children at the chronic phase of the injury as difficulties can evolve into both positive and negative outcomes.

Table 3. Total score of the 11 participants with mTBI and their parents for the PCSI questionnaire at pre-injury and the PCSI, LIFE-UK and SAB questionnaires at both measuring times (T1 and T2).

Questionnaires		**Life-UK**	**SAB**	**PCSI-Children**			**PCSI -Parent**		
				Pre-injury	Time 1	Time 2	Pre-injury	Time 1	Time 2
mTBI01	Time 1	67	39	6	12	8	28	88	20
	Time 2	66	39						
mTBI02	Time 1	78	57	0	3	4	0	8	8
	Time 2	74	57						
mTBI03	Time 1	70	41	1	20	1	1	52	24
	Time 2	87	28						
mTBI04	Time 1	66	48	9	22	8	24	22	25
	Time 2	74	48						

mTBI05	Time 1	59	55	2	19	21	0	6	4
	Time 2	68	50						
mTBI06	Time 1	65	36	0	4	6	12	46	42
	Time 2	66	34						
mTBI07	Time 1	85	43	1	2	6	6	6	15
	Time 2	84	43						
mTBI08	Time 1	45	58	3	21	7	6	103	4
	Time 2	64	58						
mTBI09	Time 1	88	51	0	3	1	7	26	0
	Time 2	90	51						
mTBI10	Time 1	81	53	0	15	1	0	66	2
	Time 2	82	53						
mTBI11	Time 1	88	25	1	2	0	15	17	35
	Time 2	85	24						

In children, the prevalence of auditory difficulties following mTBI has yet to be established. However, multiple studies in adults and in children with other severities of TBI generally report a high prevalence of auditory difficulties (Cockrell & Gregory, 1992; De Godoy et al., 2022; Gosselin et al., 2006; Hoover et al., 2017; Thompson et al., 2018; Vander Werff & Rieger, 2019a). In their cohort of 8 to 16 years old children with mTBI, Thompson and collaborators (2018) reported that most of their participants had difficulty in noise. In children with moderate to severe TBIs, studies report between 16% (Cockrell & Gregory, 1992) and 100% (De Godoy et al., 2022) of their participants having central auditory difficulties. In adults, mTBI studies report that up to 85% of their participants with mTBI present auditory processing difficulties (Hoover et al., 2017). In the current results, more than 50% of the sample dealt with auditory implications three months after the injury. When referring to difficulties associated to the failed tests in the current study, tests of the temporal processing abilities were the most failed (see Table 1 – PPST, DPT and GIN). Such difficulties can impact children's abilities to recognize certain aspects of speech (i.e.: intonation, stress or rhythm) or difficulties extracting the important information from the small gaps in noise (Bellis, 2003). Children can have difficulties extracting key words from message or understanding information delivered via the prosody aspect of speech (Bellis, 2003).

Furthermore, girls are potentially at greater risk of developing post-mTBI symptoms and have more lasting effects of the mTBI (Desai et al., 2019; Fried et al., 2022; Ponsford et al., 2011). These sex differences have yet to be fully understood but could be linked to delayed access to specialized care (Desai et al., 2019), the combination with pre-existing conditions (Fried et al., 2022) or even genetic factors (Ponsford et al., 2011). Only two girls (mTBI02 and mTBI05) were included in the current study. Both participants failed at least two tests at both measure times and, therefore, they met the criteria 1 for an APD diagnosis. Such results, while not generalizable, indicate the need for further investigation of mTBI's impact on auditory processing in girls.

When comparing individual auditory results to cognitive results, there were no systematic results pattern (see Table 2). Individual results for the cognitive screening show that children in both groups are varied and not necessary in line with auditory results as children who pass auditory tests do not necessary pass the cognitive screening and vice-versa. When observing individual data (see Tables 1 and 2), different patterns of results appear. To illustrate this, mTBI01, mTBI10 and mTBI11 were compared. Participant mTBI01 had no difficulties with passing all auditory tests at both measure times, but failed several cognitive screening subscales at T1. This result is different from both mTBI10 and mTBI11. Participant mTBI10 had mild difficulties with the cognitive screening at T1 only and failed several auditory tests at both measure times. Participant failed auditory tests at T1 only but failed several cognitive subscales at both measure times. These results suggest that behavioural tests, such as the cognitive screening, were not sensitive enough to distinguish between children with and without mTBI in the context of the current study and require further investigation and testing with children following their first mTBI.

Perception of children and their parents of listening behaviours were also considered. The two listening behaviour questionnaires, Life-UK and SAB, conducted with children and their parents, did not yield significant results. The absence of significant differences between groups could suggest that perceived listening behaviours agree with electrophysiological results. However, scores for the questionnaires were highly variable and average scores were lower for children with mTBI for each questionnaire at both measure times (see Table 4). This strictly stems from the observation of the current results. A greater number of participants could provide a better understanding of these results and reveal if they are spurious or not.

Table 4. Listening behaviours questionnaire scores (mean and standard deviation) for children and their parents in both groups at both measure times.

Questionnaires		mTBI		Control	
		mean	SD	mean	SD
SAB	Time 1	46	10	50	5
	Time 2	44	12	49	5
LIFE-UK	Time 1	72	8	78	5
	Time 2	76	10	82	4

4.2. Electrophysiological experiment

This study included a combination of two stimuli, a verbal /da/ and a tonal 1000 Hz and two noise conditions, a +15 dB SNR white noise and a +5 dB SNR white noise. Those stimuli resulted into six conditions, two quiet conditions and four noise conditions. For this experiment, both time-locked responses and ITPC values were analysed at three distinct electrodes (C5, Cz and C6). In order to decide on those recording and analysis parameters, a pre-experiment was conducted with typically developing school-aged children and young adults. A combination of two stimuli (/da/ and 1000 Hz), two noises (babble and white noise) and three SNRs (+10 dB SNR, +5 dB SNR and 0 dB SNR) were utilised to create 14 listening conditions. Responses were analysed with time-locked analysis in one electrode (Cz) and time-frequency analysis with both ITPC and total power in three electrodes (T7, Cz and T8) (see Figure 4, Chapter 1. Introduction p.17). Results indicated that the only significant group difference was a longer latency of the waveform N2 in the control group compared to the group with mTBI, especially for the right electrode, located at the right central area above the temporal lobe (see Figure 1).

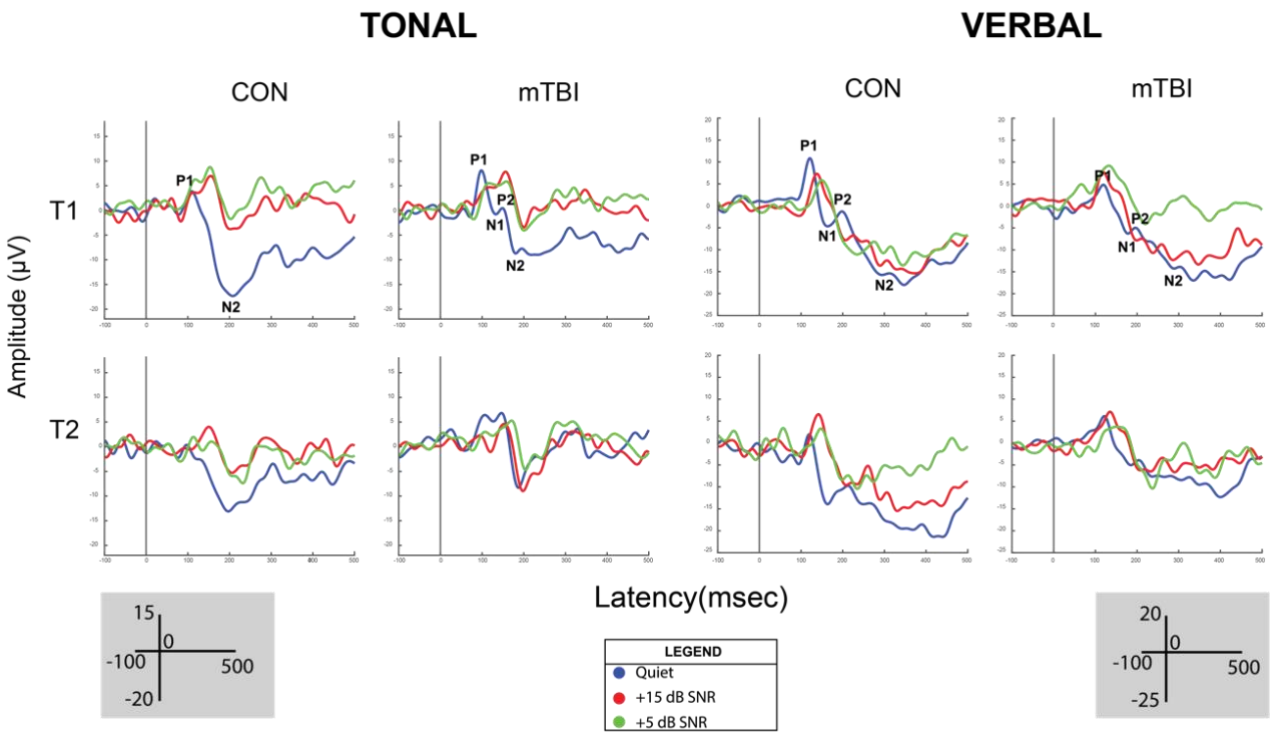

Figure 1. Grand averages of the group of children with mTBI and the control group (CON) at the C6 electrode for the tonal and verbal stimuli at the three listening conditions.

This group difference was explained in Article 4 (p. 153-154) with maturational intersubject variability as well as the small sample size. Unfortunately, no normative data is available for the electrophysiological responses recorded in the current study. The pairing of age- (at a maximum of ± 4 months) and sex-matched controls with participants with mTBI was conducted to palliate this lack of norms. However, the obtained results make interpretation difficult.

Furthermore, when observing the individual ALRs data, intersubject variability is evident. Figure 2 shows that the difference in wave maturation for the tonal stimulus at the left electrode in two children with the same age, located at the left central area above the temporal lobe, is staggering. For one participant with mTBI (mTBI01), four peaks (P1, N1, P2, and N2) were present and mature, but for the matched control CL01, only two peaks (P1 and N2) were identifiable. The central auditory system goes through profound maturational changes from childhood into adulthood (Devous et al., 2006; Paus et al., 1999; Ponton et al., 2000; Wunderlich et al., 2006). Changes specific to the ALRs generally pertain to the genesis of the N1-P2 complex (Ponton et

al., 2000; Wunderlich et al., 2006). In young children, the P1 and N2 wave components dominate the ALRs. Around the age of 9-10 years old, the N1-P2 complex appears with increasing amplitudes (Ponton et al., 2000; Wunderlich et al., 2006). With these changes, P1 and N2 amplitudes and P1 latency reduce whereas N2 latency increases (Ponton et al., 2000; Wunderlich et al., 2006). These changes happen around the same time for all children, but specific inter-individual differences are present and clearly exemplified in Figure 2. This indicates that while two children may be 9 years and 7 months old, the timeline of the abrupt and more gradual changes happening in their auditory systems may differ between them, making the comparison of their recorded responses difficult as their waves have different configurations.

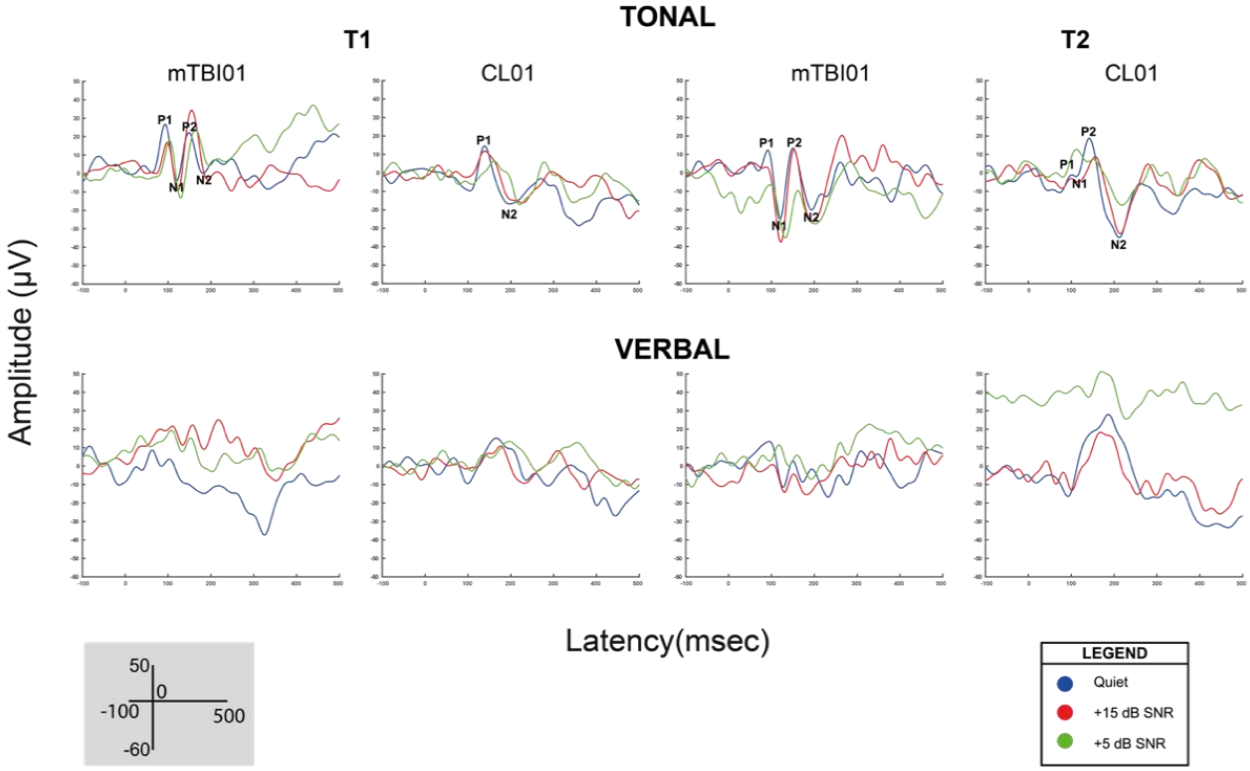

Figure 2. Individual averages of ALRs at the left electrode C5 for the tonal and the verbal stimuli in all listening conditions (Quiet, +15 dB SNR, +5 dB SNR) for the participants with mTBI (mTBI01) and the matched control (CL01).

Another example of participant differences can be seen in wave component amplitudes for mTBI03 and CL03. Participant mTBI03 had larger P1 amplitude values than the matched control CL03, but CL03 had greater N2 amplitude values than mTB03 (Figure 3).

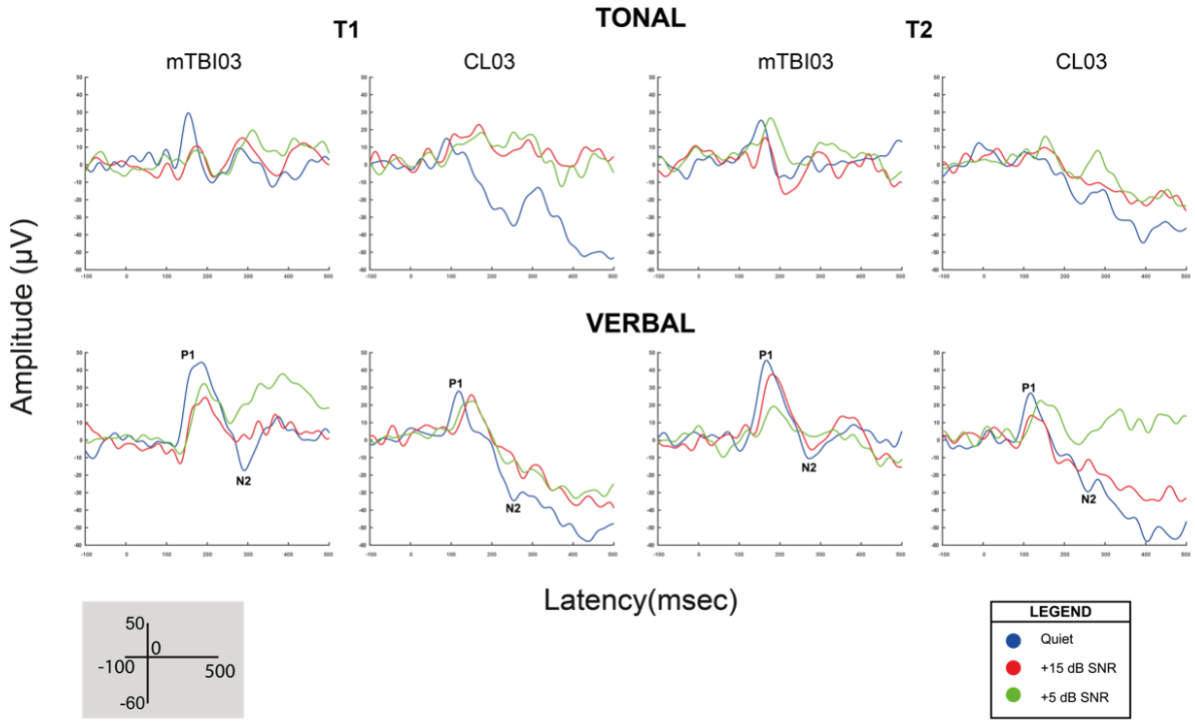

Figure 3. Individual averages of ALRs at the left electrode C5 for the tonal and the verbal stimuli in all listening conditions (Quiet, +15 dB SNR, +5 dB SNR) for the participant with mTBI (mTBI03) and the matched control (CL03).

Such variability, even in closely matched participants combined with the small sample size, could contribute to the lack of group differences reported between mTBI children and the controls for specific noise-related conditions. The results were coherent with those of previous studies regarding the effects of the type of stimulus and SNR on overall responses (Benítez-Barrera et al., 2021; Billings et al., 2011; Koerner & Zhang, 2015; Maamor & Billings, 2017). ALRs and phase synchronization analysis results were generally stable between measure times, also reported in the other studies (Ponton et al., 2000; Yordanova et al., 2002).

The current thesis detailed behavioural and electrophysiological results coming from two experiments, but data was collected from the same participants. Behavioural tests reported significant differences between groups, with mTBI participants performing more poorly than controls. Seldom electrophysiological differences did not identify a neurophysiological marker of auditory dysfunctions caused by the mTBI. In a sense, results from both experiments agreed with the current literature. mTBI is complex and heterogeneous, and a first injury can but does not

necessarily have a lasting effect on auditory function in children. As behavioural auditory processing tasks can involve language and cognition abilities to varying degree, it is possible that abnormal scores of theses behavioural tasks could be related, in part, to cognitive and language issues following mTBI. This could explain why the impacts of the mTBI were not observed on both types of tests.

4.3. Clinical implications and future directions

The current thesis is one of the steps aimed at contributing to the development of specific clinical guidelines in audiology for identification, managing and treating mTBI in school-aged children. Overall, while not offering definitive answers regarding how central auditory processing is affected in school-aged children, the results obtained in the current thesis can inform the next steps regarding auditory research in mTBI children. With behavioural results being significant but not ALR results, further exploration is needed with both measure types, as suggested below.

4.3.1. Behavioural measures

The current thesis could not establish a specific test battery and population type for auditory deficits post-mTBI. Nonetheless, the results indicated that children post-mTBI may have auditory impairments, so a central auditory processing evaluation should be conducted. When selecting tests to build a battery, temporal processing tests, such as the PPST, DPT or GIN, need to be taken into consideration. These tests were commonly failed in the current study by participants with mTBI, and a confirmation study with a more significant number of children could reaffirm and expand the current results. Speech-in-noise tests showed poorer results in children with mTBI when compared to controls in other studies, specifically in English (Thompson et al., 2018) and also in adults (Vander Werff & Rieger, 2019a). The lack of group significance for the TMB in the current study indicates that further French speech-in-noise test investigation is required. While test choice is more restricted in French, specific tests such as the Synthetic Sentence Identification-Ipsilateral Competing Message (SSI-ICM) (Lynch & Normandin, 1983), the FrBio Sentence Test (Bergeron et al., 2019) or an adaptation in Quebec French of the “Vocale Rapide dans le Bruit” (Fontan & Desreumaux, 2024) from France could be explored in children with mTBI. A better understanding of the impacts of mTBI on children is needed, including the specific evaluation and

the path to intervention, rehabilitation, or remediation. Expanding the knowledge of how children's auditory systems can be affected by mTBI may help refine the intervention.

Recommended interventions can include both top-down and bottom-up interventions (Bellis, 2003; Bellis & Anzalone, 2008; Bigras et al., 2024). On the one hand, top-down interventions generally refer to meta-cognitive listening strategies that can be taught to children to help them take charge of their communication and resolve communication breakdowns. On the other hand, bottom-up interventions refer to auditory training where protocols are prepared to train auditory abilities or to the use of assistive listening devices such as the FM system which can help in school to increase the SNR (Bellis, 2003). In their recent scoping review, Bigras and collaborators (2024) commented on interventions for school-aged children with APD. They listed top-down and bottom-up interventions available for all types of auditory difficulties. Among those interventions, specific temporal auditory training has been reported efficient to reduce difficulties and increase performance on tests of temporal processing (Nayana & Kumar, 2024). While this intervention was completed with children with auditory difficulties not related to mTBI, they can help guide the interventions employed with children with auditory difficulties following mTBI.

Further exploration of the questionnaires is also warranted. No significant differences were reported, but overall averages were poorer in the mTBI compared to the peer control. The Life-UK and the SAB could be utilized with a greater sample size. Additionally, auditory-specific items for a mTBI-specific questionnaire (Concussion Symptom Subtype Inventory) have been developed for adults (Koerner et al., 2022) but could be explored and validated with children.

4.3.2. Electrophysiological measures

The results of the current electrophysiological experiment open the door for much further exploration. For both ALRs and ITPCs, recording the AEPs in noise when participants are doing an active task could help better understand noise's impacts on auditory processing. An active task would permit a more direct comparison between behavioural performance in noise and the effect of noise on AEPs. For example, this could help to understand how SNR-related amplitude and latency changes translate to auditory detection or identification in those same SNRs. Additionally, the most failed behavioural tests were temporal processing-related tests. Exploring a paradigm associated to temporal processing, such as gap detection, could be warranted and potentially

identify a neuromarker of auditory dysfunction related to mTBI, as the behavioural counterpart was one of the auditory tests failed by some of the children with mTBI.

In the current study, variability between 8-12 years old was representative of what is seen in the literature (Ponton et al., 2000; Wunderlich et al., 2006). Having separate normative measures for children ages 8, 9, 10, 11, and 12 could help reduce the effect of intersubject variability that is significantly present in school-aged children and in the identification of slight differences following an event such as a mTBI. Such normative data could also provide clinical information for pass-fail results, helping in the classification of children's results post-mTBI. The availability of objective normative data could also be a great help, especially for difficult-to-test or diagnose patients. While not integrated into the clinic yet, objective speech in noise evaluation is warranted. Although speech in noise difficulties are the main reasons people consult in audiology, no universal evaluations currently exist. Developing an electrophysiological protocol could circumvent multiple problems, such as the language barrier, inability to respond or malingering. This tool could give clinicians and researchers further insight into how the brain processes sounds and language. It could be utilized in populations that are harder to test with a conventional test battery, such as children with comorbidities like ADHD or learning or language impairment. It would help decipher how the auditory system processes sounds, especially in non-ideal situations, when difficulties following a mTBI are thought to lie. Moreover, further exploration of the temporal evoked potentials, such as the T-complex could help in investigating such differences. As T-complex has been utilized to decipher between controls and children with conditions such as attention deficit and hyperactivity disorder (ADHD) (Gomes et al., 2012) or language impairment (Shafer et al., 2011) successfully, it could be used in the future with mTBI

Further EEG analysis, such as functional connectivity (FC) at rest, could be explored. Functional connectivity is defined as the temporal connections between the different regions of the brain (Friston, 2011). When measured with EEG, it is another avenue to investigate and better understand the impact of mTBI on brain function in children. Analysis of functional cortical connectivity has been widely used to measure dysfunction in groups with neurological (Tcheslavski & Beex, 2006), cognitive (Adeli et al., 2008; Handayani et al., 2018) or psychiatric (Velikova et al., 2010) disorders. A few studies have been interested in documenting this measure in adults with mTBI (Sponheim, 2011; Thatcher et al., 1989; Thornton, 2003). The conclusions of

these studies converge and show a reduction in connectivity in specific frequency bands: beta (Sponheim, 2011; Thornton, 2003), gamma and delta (Sponheim, 2011). The results of Thatcher et al. (1989) indicated that EEG phase and coherence are the best predictors of the extent of brain damage. While beyond the scope of the current thesis, a scoping review was conducted and revealed a lack of available studies regarding FC in school-aged children (see Appendix B). The review's results demonstrated that FC assessment of EEG in adolescents is promising as differences between mTBI and controls are identified. Results also indicated that FC could be employed in return-to-activity assessment as it can detect changes in connectivity over time.

4.4. Delays and limitations

The current thesis has limitations. On the one hand, it is conceivable that a subset of participants in this study had auditory difficulties preceding the mTBI. Based on self-reported results, pre-existing conditions and diagnoses were excluded from the study. However, no baseline was established before the injury. With more than 36% of the participants in the mTBI group presenting with persevering auditory difficulties more than three months after the injury, it is possible that certain participants had auditory difficulties preceding the current study. Moreover, three children in the control group were excluded as they failed auditory processing tests. Such a choice was made to have the most uniform and representative group of controls. Nevertheless, it is a possibility that the group differences reported in Chapter 2 were inflated due to this choice. In subsequent studies, a greater number of participants in both groups and the omission of this exclusion criteria could help in creating a more realistic and representative picture of the impacts of mTBI on children.

On the other hand, children in the mTBI group were excluded if they had a history of head injury prior to the one sustained for the study. It is known that patients who undergo an mTBI are more at risk for additional mTBIs, and additional sustained mTBIs increase the risk of suffering from persistent effects following the mTBI (Graham et al., 2014). Exclusion of these children prevented the observation of how multiple mTBIs affect their auditory function and how these effects persist.

The current research project was strongly affected by the COVID-19 pandemic. The PhD program started in 2018, before the pandemic, and initial recruitment was projected for the summer of 2020. At the beginning of the pandemic, during the lockdown, it was not at all possible to access the

laboratory at the University of Ottawa and the necessary equipment (Electroencephalogram) for carrying out this project. This inability to leave the house delayed the implementation of the evaluation protocol for the project. None of the experiments conducted in the current thesis could be carried out remotely. With this reliance on participant presence, the evolution of the pandemic and Public Health guidelines directly impacted the implementation of the project, slowing down and halting activities during the pandemic. Furthermore, while the equipment needed to be transferred from the University of Ottawa to the University of Montreal and the project being carried out there, it was impossible to collect and move it then. Over the next two years (2020 to 2022), lockdowns, curfews, and limited interprovincial transit have slowed down all research activities, such as data collection and recruitment of participants.

Initially, the recruitment was planned with only the CHUSJ's emergency room patients, where data indicated that 280 children in the selected age group had been seen for mTBI (data received from Dr. Jocelyn Gravel, pediatric emergency doctor) in the year preceding the planned start date for the current thesis' project. As only about 10% of contacted people participate in a study (Bachenheimer & Brescia, 2007), the plan was to recruit 30 participants with mTBI (~ 10% of the emergency visits) and 30 controls for a total of 60 participants. This was planned in 2019. In 2020 when the project was set to start, the CHUSJ emergency rooms were understandably overwhelmed and unable to recruit potentials candidates with mTBI during the long periods of increased medical needs following COVID. Moreover, the control participants' recruitment was supposed to occur in the community through sports teams and community centers, and the cancellation of these activities or the closure of venues reduced recruitment power. Twenty-six participants were recruited for the main study, and twenty-one participated. For mTBI participants, between the CHUSJ and the Montreal Children's Hospital (involved as recruitment was not progressing), 259 children were screened in the emergency room as potential candidates, with 148 eligible to participate. Of those, 13 agreed, and 135 refused to participate, leading to a recruitment success rate of 8%. As two participants were excluded, eleven were included as mTBI participants. This rate is less than half of what was expected during the project's inception in 2019. The control participant was recruited in the community and at the CHUSJ external Orthopedic Clinic. Seventy-nine children were screened, and 63 children were eligible. Thirteen children were recruited, and fifty refused to participate. The recruitment success rate for children in the control group was 16%.

As three participants were excluded, ten were included in the control group. Overall, the current study was long, impacting recruitment and choices.

CHAPTER 5. Conclusion

The current dissertation's results have brought forth new knowledge regarding auditory processing in adverse listening conditions for school-aged children and how the auditory abilities/function were affected by mTBI. As not all children recover spontaneously from mTBI, testing according to symptomology and difficulties is recommended. Results from the behavioural experiment showed that specific central auditory tests seem more sensitive to mTBI than results from the electrophysiological experiment, where no reliable differences between the group of children with mTBI and the control group could be identified. Behavioural auditory tests, specifically temporal processing tests, should be investigated as an option to screen for auditory difficulties in children with mTBI.

Electrophysiological results suggested that additional research is needed. AEPs in noise responses (ALRs and ITPC) were not different between children with and without mTBI, but they could be used to monitor rehabilitation. Exploring alternate EEG analysis methods, such as FC analysis, can help better to understand how mTBI impacts the brain and, therefore, the central auditory system.

Future studies should include a greater number of participants and adapt both the behavioural and electrophysiological test batteries. Moreover, while this project did not address intervention and treatment following mTBI, future studies should look at the additional goal of developing auditory-specific interventions/treatments, which would be the next step in helping children with mTBI and identified auditory difficulties.

AUTHORS CONTRIBUTIONS

Fauve Duquette-Laplante was the leading investigator for the five articles included in the current thesis. Fauve Duquette-Laplante was involved in every part of the project, from funding acquisition to ethics, data collection and analysis and preparation and review of each presented manuscript. For the first article, available in Chapter 2 p. 20-50, entitled *Central auditory and cognitive abilities after mild Traumatic Brain Injury in school-aged children* (published 2024), she analyzed the data and authored the manuscript, which was supported by professors Amineh Koravand and Benoît Jutras. The co-authors, Miriam Beauchamp, Jocelyn Gravel, Justine Ratelle and Isabelle Gagnon, revised the manuscript. The authors' contributions are detailed p. 42 in a CreDit format. Articles 2, 3 and 4 are available in Chapter 3. In Article 2, *Exploring the differences between an immature and a mature human auditory system through auditory late responses in quiet and in noise* (published 2024), p. 52-87, Fauve Duquette-Laplante authored the majority of the manuscript supported by two audiologists who assisted with data collection: Noémie Néron, who also assisted with data analysis of the original draft of the results section and Sandra Fortin who also assisted with the manuscript revision. Professors Amineh Koravand and Benoît Jutras supported data analysis and the reviewing and correcting of the manuscript. The authors' contributions are detailed p. 80-81 in a CreDit format. In Article 3, *The impact of noise on auditory processing in children and adults: a time-frequency analysis perspective* (in preparation), p. 88-131, Fauve Duquette-Laplante authored the manuscript supported by audiologist Aurélie Belleau-Matte, who provided support for the data collection and analysis as well as authoring the initial draft. Professors Amineh Koravand, Benoît Jutras and Boutheina Jemel supported data analysis and manuscript revision. The final manuscript revision from all included collaborators is still pending. Detailed authors' contributions are available on p. 117 in a CreDit format. In Article 4, *Mild traumatic brain injury in school-aged children: Insights into auditory processing in noise via auditory evoked potentials* (in preparation), p. 133-173, Fauve Duquette-Laplante authored the manuscript supported by audiology student Marianne Dubuc, who aided in data collection and analysis. Professors Amineh Koravand, Benoît Jutras and Boutheina Jemel provided support for data analysis. Professors Amineh Koravand and Benoît Jutras revised the manuscript. The final manuscript revision from all included collaborators is still pending. Detailed authors' contributions

are available on p. 156-157 in a CreDit format. The last article in this current thesis is available in Appendix B, p. XXXVI-LXIV, *Brain functional connectivity in children with a mild traumatic brain injury: A scoping review* (published 2023); Fauve Duquette-Laplante, who led data collection and extraction and authored the manuscript, was supported by Melissa MacAskill, an audiologist who co-authored the article. Professors Amineh Koravand, Benoît Jutras, and Boutheina Jemel supported revising the manuscript.

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APPENDIX

Appendix A

A.1. Letters of Support

Université de Montréal

École d'orthophonie et d'audiologie

Le 11 août 2020,

Comité d'éthique de la recherche
CHU Sainte-Justine
3175, Chemin de la Côte-Sainte-Catherine
Montréal, Québec
H3T 1C5

Objet : Lettre d'appui pour la collecte de données du projet de recherche intitulé : *Le traitement de l'information auditive d'enfants d'âge scolaire ayant subi un traumatisme crâniocérébral léger*

Mesdames/ Messieurs

Je vous confirme que je donne la permission à monsieur Benoît Jutras, professeur titulaire à l'École d'orthophonie et d'audiologie et chercheur au Centre de recherche du CHU Sainte-Justine et à son équipe de recherche d'utiliser les équipements dans les laboratoires d'audiologie de notre École pour effectuer la collecte de données dans le cadre le projet de recherche nommé ci-haut. Cette permission est conditionnelle à l'obtention du certificat d'ouverture émis par le comité de reprise des activités de recherche de l'Université de Montréal.

Si vous avez des questions à ce sujet, n'hésitez pas à me contacter. Veuillez recevoir, Mesdames/ Messieurs, mes salutations distinguées.

CHU Sainte-Justine
Le centre hospitalier universitaire mère-enfant
Université de Montréal

Montréal, le 11 novembre 2019

OBJET : Lettre d'appui au projet de recherche intitulé *Le traitement de l'information auditive d'enfants d'âge scolaire ayant subi un traumatisme crâniocérébral léger*

Chers membres du comité d'évaluation,

Par la présente, je souhaite vous communiquer mon appui en tant que chef de service et chef professionnel en orthophonie et audiologie du CHU Sainte-Justine pour le projet *Le traitement de l'information auditive d'enfants d'âge scolaire ayant subi un traumatisme crâniocérébral léger*.

Je souhaite vous assurer de notre collaboration en procédant à l'évaluation audiologique du système auditif périphérique des enfants ayant un traumatisme crâniocérébral léger qui seront référés à la clinique d'audiologie du CHU Sainte- Justine dans le cadre de cette étude, et ce moyennant un dédommagement monétaire convenu avec le chercheur responsable du projet. Nous nous engageons également à promouvoir les opportunités de transfert des connaissances qui ressortiront du projet réalisé.

Veuillez accepter, Madame, Monsieur, mes salutations distinguées.

Annie-Joëlle Fortin
Chef de service et chef professionnel en orthophonie et audiologieCHU Sainte-Justine

CHU Sainte-Justine
Le centre hospitalier universitaire mère-enfant

Université de Montréal

Montréal, 30 janvier 2020

Dr Benoit Jutras
CHU Sainte-Justine
3175 Chemin Cote Sainte-Catherine
Montréal, Qc, H3T 1C5

Objet: Support pour la tenue de l'étude *«Le traitement de l'information auditive d'enfants d'âge scolaire ayant subi un traumatisme crâniocérébral léger »*

Cher Dr Jutras,

En tant que chef du service d'urgence du CHU Sainte-Justine, il me fait plaisir de supporter votre projet d'étude visant à évaluer la présence de problèmes audiologiques parmi la population d'enfants ayant subi une commotion cérébrale.

De part leur nombre, les patients victimes de TCC légers représentent un problème de santé important pour les services d'urgence et la prévalence de ces blessures est particulièrement élevée chez les jeunes de 8 à 12 ans. Votre étude permettra d'évaluer si ces derniers ont des problèmes de traitement auditif secondaires au TCCl. Si c'est le cas, ceci pourrait expliquer les problèmes d'apprentissage reliés aux TCCl. La participation de notre service se limitera à l'identification et le recrutement d'une trentaine d'enfant avec TCCl et une trentaine de contrôles.

En vous souhaitant du succès dans vos entreprises de recherche, veuillez agréer, Dr Jutras, mes meilleures salutations.

Centre de recherche
CHU
Sainte-Justine
Le centre hospitalier
universitaire mère-enfant

Université de Montréal

Jacques L. Michaud, M.D.
Directeur de la recherche
Direction de la recherche

Téléphone : 514 345-4740

8 janvier 2020

Docteur Benoit Jutras
Centre de recherche
CHU Sainte-Justine

Objet : Concours TRAUMA 2019-2020

Docteur Jutras,

J'ai le plaisir de vous informer que votre proposition pour le concours TRAUMA 2019-2020 intitulé «Le traitement de l'information auditive d'enfants d'âge scolaire ayant subi un traumatisme crâniocérébral léger » a été recommandée pour financement. La sélection des projets a été réalisée via un mécanisme de revue pair qui a été constitué par la direction du centre de recherche. Le comité d'évaluation avait le mandat d'évaluer et de classer selon les modalités définies, les projets proposés dans le cadre du TRAUMA. Un résumé des évaluations est décrit ci-dessous.

Suite au processus d'évaluation, le comité des réviseurs a recommandé cinq projets au lieu de quatre pour financement. Le montant total de votre fonds est de $20,000. Ce montant doit être utilisé dans les deux ans suivant la date de début du financement, le 1er avril 2020. Vous devez informer vos collaborateurs et les membres de l'équipe de ce fonds. Le comité TRAUMA exigera un rapport d'étape du projet qui devra être déposé au plus tard le 30 avril 2021. Les fonds non utilisés à la fin de la première année, soit le 31 mars 2021, pourront être transférés à la deuxième année. Dans ce cas vous devrez soumettre un rapport final du projet avant le 15 avril 2022.

Mes meilleures félicitations.

Jacques L. Michaud
Directeur de la recherche
CHU Sainte-Justine

Review summary

The reviewers recognized the importance of this well-written study. The objectives were clearly articulated and the hypothesis was well justified and based on a very good literature overview. The methodology was considered appropriate with clear criteria for the analysis of the auditive data. However, the reviewers raised questions about the eligibility criteriaand choice for the age group 8-12 year. Arguments to exclude children upto 7 year were given, but it is not clear reason why children of age 13 and higher were excluded. Also, the criterion of trauma experience within a week of enrolment was not explained and may lead to the observation of acute effects or those resulting from fatigue, which is not the objective of the study.

Although reviewers have confidence that this experienced team will be able to pull of the study within the funding period, they were concerned about the adherence of children to complete the study for only such a small compensation. The total time spend to auditive evaluations adds up to 255 minutes, including sessions of 90 minutes that may cause a loss ofinterest.

The study has a clear potential to improve clinical management and intervention of children admitted to trauma, which clearly aligns with the TRAUMA competition. The applicants are encouraged to consider the points raised by the reviewers and adress them in the progress report.

A.2. Ethics approuval

Le 5 mai 2020

Objet	Approbation éthique initiale - CÉR
	2020-2618 Le traitement de l'information auditive d'enfants d'âge scolaire ayant subi un traumatisme crâniocérébral léger. Co-chercheurs : Fauve Duquette-Laplante; Amineh Koravand; Miriam Beauchamp; Jocelyn Gravel; Justine Ratelle

Bonjour,

Le Comité d'éthique de la recherche du CHU Sainte-Justine, à sa réunion plénière tenue le 26 mars 2020, a évalué le projet mentionnéen rubrique. Suite à vos réponses satisfaisantes, le Comité accorde son approbation éthique en date du 4 mai 2020.

Votre projet pourra commencer dans nos murs uniquement lorsque la personne mandatée au CHU Sainte-Justine aura émis et déposé son autorisation pour la réalisation du projet de recherche au CHU Sainte-Justine.

L'examen scientifique a été réalisé par le Programme de subvention en trauma

pédiatrique au CHU Sainte-Justine. Les documents suivants ont été

approuvés :

- Protocole de recherche non daté
- Ajouts au protocole non daté
- Formulaire d'information et de consentement
- pilote daté du 26 mars 2020 Formulaire
- d'information et de consentement sans TCCL
- daté du 26 mars 2020 Formulaire d'information et de consentement avec TCCL daté du 26 mars 2020Affiche de recrutement Facebook non datée
- Affiche de
- recrutement pilote Facebook non datée Affiche de

recrutement pilote
non datée

- Affiche de recrutement non datée
- Questionnaire LIFE-UK IHP - FR (Listening Inventories for Education UK Individual Hearing
- Profile) non daté (version française) Questionnaire Échelle des comportements auditifs non daté
- Questionnaire sur les symptômes post-traumatiques version
- parent (PCSI-P) non daté Questionnaire sur les symptômes post-
- traumatiques version enfant de 5 à 12 ans (PCSI-C) non daté
  Feuille de route infirmières datée du 17 mars 2020
- Procédure destinée aux audiologistes datée du 17 mars 2020

Les formulaires d'information et de consentement estampillés ont été déposés dans le dossier du projet. Nous vous prions de vous servir de ces versions estampillées.

Tous les projets de recherche impliquant des sujets humains doivent être réévalués annuellement. La durée de votre approbation sera effective jusqu'au **4 mai 2021**. Il est de votre responsabilité de soumettre une demande au comité pour que l'approbation éthique soit renouvelée avant la date d'expiration. Il est également de votre responsabilité d'aviser le comité dans les plus brefs délais de toute modification au projet et/ou de tout événement grave et inattendu susceptible d'augmenter le niveau de risque ou d'influer sur le bien-être du participant.

Considérez que pour une collaboration avec un tiers impliquant des transferts de fonds ou de données/matériel biologique, une entente (contrat) est nécessaire. Celle-ci doit être gérée par le Bureau des ententes de recherche.

À noter que :

- Le Comité d'éthique de la recherche du CHU Sainte-Justine (numéro FWA00021692) est désigné par le gouvernement du Québec (MSSS).
- La composition de ce comité d'éthique pour la recherche satisfait aux exigences pertinentes prévues dans le titre 5 de la partie C du Règlement sur les aliments et drogues.
- Le comité d'éthique de la recherche exerce ses activités d'une manière conforme aux Bonnes pratiques cliniques, à l'Énoncé de politique des trois conseils : Éthique de la recherche avec des êtres humains, au Plan d'action ministériel en éthique de la recherche et en intégrité scientifique, aux lois et règlements applicables au Québec et au Canada, ainsi qu'aux standards américains énoncés par le Code of Federal Regulations.

En vous souhaitant du succès dans la réalisation de votre projet,

Me Geneviève Cardinal
Présidente
Comité d'éthique de la recherche

CHU Sainte-Justine
Le centre hospitalier universitaire mère-enfant
Université de Montréal

Le 24 août 2020

Objet	Autorisation de réaliser la recherche
	2020-2618 Le traitement de l'information auditive d'enfants d'âge scolaire ayant subi un traumatisme crâniocérébral léger. Cochercheurs: Fauve Duquette-Laplante; Amineh Koravand; Miriam Beauchamp; Dr Jocelyn Gravel; Justine Ratelle

Bonjour,

Il nous fait plaisir de vous autoriser à réaliser la recherche identifiée en titre dans notre établissement et/ou sous ses auspices.

Cette autorisation vous est accordée sur la foi des documents que vous avez déposés auprès de notre établissement afin de compléterl'examen de convenance ainsi que la lettre du CER évaluateur. Si ce CER vous informe pendant le déroulement de cette recherche d'unedécision négative portant sur l'acceptabilité éthique de cette recherche, vous devrez considérer que la présente autorisation de réaliser la recherche dans notre établissement est, de ce fait, révoquée à la date que porte l'avis du CER évaluateur.

Notre établissement a reçu une copie de la version finale des documents se rapportant à la recherche, approuvée par le CERévaluateur.

Cette autorisation de réaliser la recherche suppose également que vous vous engagez :

1) à vous conformer aux demandes du CER évaluateur, notamment pour le suivi éthique continu de la recherche;
2) à rendre compte au CER évaluateur et à la signataire de la présente autorisation du déroulement du projet, des actes de votreéquipe de recherche, s'il en est une, ainsi que du respect des règles de l'éthique de la recherche;
3) à respecter les moyens relatifs au suivi continu qui ont été fixés par le CER évaluateur;
4) à conserver les dossiers de recherche pendant la période fixée par le CER évaluateur, après la fin du projet, afin de permettre leur éventuelle vérification;
5) à respecter les modalités arrêtées au regard du mécanisme d'identification des sujets de recherche dans notre établissement, àsavoir la tenue à jour et la conservation de la liste à jour des participants de recherche recrutés dans notre établissement. Cette liste devra nous être fournie sur demande.

La présente autorisation peut être suspendue ou révoquée par notre établissement en cas de non-respect des conditions établies. Le CER évaluateur en sera alors informé.

Vous consentez également à ce que notre établissement communique aux autorités compétentes des renseignements personnels qui sont nominatifs au sens de la loi en présence d'un cas avéré de manquement à la conduite responsable en recherche de votre part lors de la réalisation de cette recherche.

Je vous invite à entrer en communication avec moi pendant le déroulement de cette recherche dans notre établissement, si besoin est. Vous pouvez aussi contacter notre CER en vous adressant au Bureau de l'éthique de la recherche (ethique@recherche-ste-justine.qc.ca, poste 4040).

En terminant, je vous demanderais de toujours mentionner dans votre correspondance au sujet de cette recherche le numéro attribué à votre demande par notre établissement ainsi que le numéro attribué au projet de recherche par le CER évaluateur.

Veuillez accepter mes sincères salutations.
Mariana DUMITRASCU
Coordonnatrice du
Bureau de l'éthique
de la recherche
CHU Sainte-
Justine

Pour Marc Girard, M.D.
Directeur des services professionnels (DAMU)
Personne formellement mandatée au CHU Sainte-Justine pour autoriser la réalisation des projets de rercher

CHU Sainte-Justine
Le centre hospitalier universitaire mère-enfant

Université de Montréal

Autorisation du recrutement

Projet de recherche : *Le traitement de l'information auditive d'enfants d'âge scolaire ayant subi un traumatisme crâniocérébral léger*

Nom du chercheur responsable : Benoît Jutras

Service/Département : Clinique d'orthopédie

En tant que chef de service/département, j'autorise le recrutement de patients dans le service/département énoncé ci-haut.

Nom : Dr Stefan Parent
Signature :
Date : 31 juillet 2023

Centre universitaire de santé McGill | McGill University Health Centre

2022-12-13

Ms. Isabelle Gagnon, PhD
Emergency Medicine
Pediatric Trauma Program MUHC - Montreal Children's Hospital 5252 boul. de Maisonneuve O Montreal, QC
email:

Re: Final authorization to conduct your research project at the MUHC
Objet: Autorisation définitive de réaliser votre projet de recherche au CUSM

Titre du projet: Le traitement de l'information auditive d'enfants d'âge scolaire ayant subi un traumatisme crâniocérébral léger.
Project Title: Auditory processing of school-aged children with mild traumatic brain injury.

Numéro de dossier du CER évaluateur / File Number of Reviewing REB: MP-21-2020-2618
CER évaluateur / Reviewing REB : CHU Sainte-Justine
Date d'approbation éthique / REB Approval Date : 2020-05-05

Numéro de dossier CUSM / MUHC File Number: MEO-21-2023-9276
Personne contacte au CUSM / MUHC contact person:
Bureau de la Personne Mandatée (PM) Office
personne.mandatee@muhc.mcgill.ca

*** La version française suit ***

Ms. Gagnon, PhD,

We are pleased to allow you to carry out the research project, identified above, under the auspices of the MUHC.

We are writing to confirm that the study mentioned above has received all required institutional approvals, namely:

- Access to health records

This authorization allows you to perform research at the MUHC.

By granting this authorization, our institution recognizes the ethical review that was done by the REB mentioned above.

- This REB is the Reviewing REB for this project in accordance with the MSSS Cadre

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de référence des établissements publics du RSSS pour l'autorisation d'une recherche menée dans plus d'un établissement (le Cadre de référence) (the MSSS Framework); and
- This REB confirmed on the date of REB approval, see above, the positive outcome of the scientific and ethics reviews of the project.

This authorization is given on condition that you commit to:

- Respecting the provisions of the MSSS framework relevant to your research project;
- Complying with the MUHC regulatory framework (April 2016) for research involving humans, including the identification of research participants;
- Using the version of the documents relating to the research approved by the Reviewing REB, to which only administrative changes have been made and communicated to the Reviewing REB; and
- Meeting the requirements set by the Reviewing REB for ongoing ethical oversight of research.

The authorization given to you to realize the research project under the auspices of our institution will be renewed without further proceedings on the date specified by the REB assessor's decision to renew its ethical approval for this research.

Please contact the MUHC PM Office mentioned above for any questions regarding this authorization or its renewal or about administrative changes that have been made to the version of the documents relating to the research approved by the Reviewing REB.

Lastly, we ask you to refer to both study numbers assigned to your research project by our institution and by the Reviewing REB when discussing the study.

Sincerely,

Kassandy Kowalyk (see signature below)
for:
Keith Woolrich
Personne Mandatée
McGill University Health Centre | Centre Universitaire de Santé McGill

cc. Renaud Boulanger, MUHC REB Co-Chair
Geneviève Cardinal, Reviewing REB Chair
Benoît Jutras, PI who submitted to Reviewing REB

Ms. Gagnon, PhD,

Il nous fait plaisir de vous autoriser à réaliser la recherche identifiée en titre et sous les auspices du CUSM.

Nous vous écrivons pour confirmer que l'étude susmentionnée a reçu toutes les approbations institutionnelles requises, à savoir:

- Accès aux dossiers de santé

Cette autorisation vous permet de réaliser la recherche au CUSM.

Pour vous donner cette autorisation, notre établissement reconnaît l'examen éthique effectué par le CER évaluateur mentionné ci-haut.

- Ce CER agit comme CER évaluateur pour ce projet, conformément au Cadre de référence des établissements publics du RSSS pour l'autorisation d'une recherche menée dans plus d'un établissement (le Cadre de référence) ; et
- Ce CER a confirmé le résultat positif de l'examen éthique et scientifique du projet à la date d'approbation éthique mentionnée ci-haut.

Cette autorisation vous est donnée à condition que vous vous engagiez à:

- Respecter les dispositions du Cadre de référence se rapportant à votre recherche;
- Respecter le cadre réglementaire de notre établissement sur les activités de recherche, notamment pour l'identification des participants à la recherche;
- Utiliser les versions des documents se rapportant à la recherche approuvées par le CER évaluateur, les seuls changements apportés, si c'est le cas, étant d'ordre administratif et identifiés de façon à ce que le CER évaluateur puisse en prendre connaissance ; et
- Respecter les exigences fixées par le CER évaluateur pour le suivi éthique de la recherche.

L'autorisation qui vous est donnée ici de réaliser la recherche sous les auspices de notre établissement sera renouvelée sans autre procédure à la date indiquée par le CER évaluateur dans sa décision de renouveler son approbation éthique de cette recherche.

Pour toute question relative à cette autorisation ou à son renouvellement ou au sujet de changements d'ordre administratifs qui auraient été apportés à la version des documents se rapportant à la recherche approuvée par le CER évaluateur, veuillez communiquer avec le bureau de la PM mentionné en rubrique.

En terminant, veuillez toujours mentionner dans votre correspondance au sujet de cette recherche le numéro attribué à votre demande par notre établissement ainsi que le numéro attribué au projet de recherche par le CER évaluateur.

En espérant le tout à votre entière satisfaction.

Cordialement,

Kassandy Kowalyk

Kassandy Kowalyk
for:
Keith Woolrich
Personne Mandatée
Centre universitaire de sante

Université d'Ottawa
Bureau d'éthique et d'intégrité de la recherche

University of Ottawa
Office of Research Ethics and Integrity

CERTIFICAT D'APPROBATION ÉTHIQUE | CERTIFICATE OF ETHICS APPROVAL

Numéro du dossier / Ethics File Number	H-07-20-5557
Titre du projet / Project Title	Impact du traumatisme crâniocérébral léger sur le traitement de l'information auditive centrale
Type de projet / Project Type	Thèse de doctorat / Doctoral thesis
Statut du projet / Project Status	Renouvelé / Renewed
Date d'approbation (jj/mm/aaaa) / Approval Date (dd/mm/yyyy)	02/11/2020
Date d'expiration (jj/mm/aaaa) / Expiry Date (dd/mm/yyyy)	12/04/2024

Équipe de recherche / Research Team

Chercheur / Researcher	Affiliation	Role
Fauve DUQUETTE-LAPLANTE	École des sciences de la réadaptation / School of Rehabilitation Sciences	Chercheur Principal / Principal Investigator
Amineh KORAVAND	École des sciences de la réadaptation / School of Rehabilitation Sciences	Superviseur / Supervisor
Isabelle GAGNON	McGill University	Co-chercheur / Co-investigator
Miriam BEAUCHAMP	U.Montreal	Collaborateur / Collaborator
Jocelyn GRAVEL	CHU Sainte-Justine	Collaborateur / Collaborator
Benoît JUTRAS	UNiversité de Montréal	Co-superviseur / Co-supervisor
Justine RATELLE	CHU Sainte-Justine	Collaborateur / Collaborator

Conditions spéciales ou commentaires / Special conditions or comments

Université d'Ottawa
Bureau d'éthique et d'intégrité de la recherche

University of Ottawa
Office of Research Ethics and Integrity

Le Comité d'éthique de la recherche (CÉR) de l'Université d'Ottawa, opérant conformément à l'*Énoncé de politique des Trois conseils* (2014) et toutes autres lois et tous règlements applicables, a examiné et approuvé la demande d'éthique du projet de recherche ci-nommé.

L'approbation est valide pour la durée indiquée plus haut et est sujette aux conditions énumérées dans la section intitulée "Conditions Spéciales ou Commentaires". Le formulaire « Renouvellement ou Fermeture de Projet » doit être complété quatre semaines avant la date d'échéance indiquée ci-haut afin de demander un renouvellement de cette approbation éthique ou afin de fermer le dossier.

Toutes modifications apportées au projet doivent être approuvées par le CÉR avant leur mise en place, sauf si le participant doit être retiré en raison d'un danger immédiat ou s'il s'agit d'un changement ayant trait à des éléments administratifs ou logistiques du projet. Les chercheurs doivent aviser le CÉR dans les plus brefs délais de tout changement pouvant augmenter le niveau de risque aux participants ou pouvant affecter considérablement le déroulement du projet, rapporter tout évènement imprévu ou indésirable et soumettre toute nouvelle information pouvant nuire à la conduite du projet ou à la sécurité des participants.

The University of Ottawa Research Ethics Board, which operates in accordance with the *Tri-Council Policy Statement* (2014) and other applicable laws and regulations, has examined and approved the ethics application for the above-named research project.

Ethics approval is valid for the period indicated above and is subject to the conditions listed in the section entitled "Special Conditions or Comments". The "Renewal/Project Closure" form must be completedfour weeks before the above-referenced expiry date to request a renewal of this ethics approval or closure of the file.

Any changes made to the project must be approved by the REB before being implemented, except when necessary to remove participants from immediate endangerment or when the modification(s) only pertain to administrative or logistical components of the project. Investigators must also promptly alert the REB of any changes that increase the risk to participant(s), any changes that considerably affect the conduct of the project, all unanticipated and harmful events that occur, and new information that may negatively affect the conduct of the project or the safety of the participant(s).

Germain ZONGO
Responsable d'éthique en recherche / Protocol Officer
Pour/For Daniel LAGAREC Président(e) du/ Chair of the Comité d'éthique de la recherche en sciences de la santé et sciences / Health Sciences and Sciences Research Ethics Board

Le traitement de l'information auditive d'enfants d'âge scolaire ayant subi un traumatisme crâniocérébral

A.3. Consent Forms

FORMULAIRE D'INFORMATION ET DE CONSENTEMENT

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1) Titre de l'étude

Le traitement de l'information auditive d'enfants d'âge scolaire ayant subi un traumatisme crâniocérébral léger

2) Nom des chercheurs

Benoît Jutras, Ph.D., Chercheur, Centre de recherche, CHU Sainte-Justine; Professeur titulaire, École d'orthophonie et d'audiologie, Université de Montréal
Fauve Duquette-Laplante, M.H.Sc., Audiologiste, Étudiante au doctorat, Sciences biomédicales, option audiologie, Université de Montréal et Sciences de la réadaptation, Université d'Ottawa
Amineh Koravand, Ph.D., Professeure agrégée, Programme d'audiologie et d'orthophonie de l'Universitéd'Ottawa
Miriam Beauchamp, Ph.D., Chercheure**,** Centre de recherche, CHU Sainte-Justine; Professeure agrégée, Département de psychologie, Université de Montréal
Jocelyn Gravel, M.D., Pédiatre urgentologue, CHU Sainte-Justine; Professeur agrégé de clinique, Département de pédiatrie, Université de Montréal
Justine Ratelle, M.P.A., Audiologiste, CHU Sainte-Justine

3) Organisme subventionnaire

Concours Trauma 2019-2020, CHU Sainte-Justine

4) Invitation à participer à un projet de recherche

Des membres de l'équipe de recherche en audiologie et en neurotraumatologie du CHU Sainte-Justine et de l'Université d'Ottawa veulent documenter les capacités auditives d'enfants ayant subi un traumatisme crâniocérébral léger (TCC-L), dans le cadre de la thèse de l'étudiante au doctorat, Fauve Duquette-Laplante. On en connaît peu sur les difficultés auditives que peuvent vivre des enfants ayant subi un TCC-L et leurs impacts au quotidien. Il apparaît donc important de déterminer les dysfonctions auditives de ces enfants afin d'intervenir le plus rapidement possible et de façon appropriée pour réduire ces impacts. Nous vous invitons à lire ce formulaire d'information afin de décider si vous êtes intéressé à participer à cette étude.

5) Nature de ce projet

Le traumatisme crâniocérébral léger (TCC-L) est une blessure fréquente chez les enfants. Il peut laisser, entre autres, des séquelles comme une perte auditive. Toutefois, d'autres symptômes auditifs sont rarement évalués, principalement ceux reliés aux capacités auditives de haut niveau faisant appel au fonctionnement de la partie neurale du système auditif (du tronc cérébral jusqu'au cerveau, appelé système auditif central). Il est possible d'évaluer ces symptômes à l'aide de mesures de l'activité du cerveau qui vérifie l'intégrité des structures du système auditif. La présente étude pilote vise à développer un protocole qui utilise ces mesures afin de déterminer comment des signaux auditifs sont traités par le cerveau lorsqu'ils sont présentés dans le silence et quand ils le sont dans le bruit. Les résultats de cette étude pilote serviront de guide pour poursuivre la rechercheauprès

d'enfants ayant eu un TCC-L. Ce projet pilote comprendra quinze enfants et quinze adultes qui n'ont paseu de blessure à la tête et qui n'ont pas non plus de problèmes auditifs soupçonnés. Vous en ferez partie si vous remplissez les critères d'admissibilité.

6) Déroulement

Mesures. Si vous êtes admissible à la recherche, il aura une évaluation de votre audition et une mesure de l'activité cérébrale, appelée électrophysiologie. Ces évaluations s'échelonneront sur une rencontre d'une durée totale de deux heures trente minutes, incluant des pauses. Ces rencontres seront prévues selon vos disponibilités et se dérouleront à l'École d'orthophonie et en audiologie de l'Université de Montréal.

Évaluation de l'audition

Une évaluation de l'audition sera effectuée. Vous serez assis dans une cabine où le niveau de bruit ambiant est contrôlé, appelée cabine insonore. À l'aide d'écouteurs, nous présenterons des sons pour déterminer vos seuils d'audition. Nous vérifierons aussi comment vos tympans bougent à l'aide d'une légère pression envoyée dans le conduit auditif. Nous vous demanderons également de répéter des séries de mots présentés individuellement. Cette partie prendra environ trente minutes. Les résultats à ces tests doivent être normaux afin de poursuivre votre participation à la présente étude.

Mesure de l'activité du cerveau (électrophysiologie)

Durant cette mesure, vous serez assis confortablement et on placera un bonnet sur sa tête. Ce bonnet comporte des petits capteurs métalliques (électrodes) qui seront en contact avec le cuir chevelu. Ces capteurs servent à mesurer l'activité électrique du cerveau mais n'influenceront d'aucune façon le fonctionnement de votre cerveau. Il n'y a pas de douleur associée à la pose du bonnet. Tout au plus, vous pourrez être incommodé par le temps nécessaire à l'installation et par une légère sensation d'irritation du cuir chevelu lors de la préparation à la pose des électrodes. Il faut frotter le cuir chevelu avec un gel pour que les électrodes du bonnet captent plus facilement les ondes du cerveau. Quatre capteurs avec du gel seront aussi installés autour de vos yeux. À la suite de l'installation du casque, des écouteurs seront placés dans le conduit de chaque oreille et serviront à présenter des sons. Vous n'aurez qu'à rester calme et éveillé durant cette évaluation. Cette évaluation prendra environ deux heures, dont 45 minutes dédiées à la pose du casque.

7) Avantages et bénéfices

Vous bénéficierez d'une évaluation de votre audition. Les résultats vous seront transmis oralement. Dans le cas de résultats anormaux, des références vous seront données si le problème n'est pas connu de votre part. Dans le futur, pour l'ensemble des enfants aux prises avec un TCC-L, les retombées attendues incluent une meilleure connaissance de leurs difficultés. Les résultats pourraient éventuellement orienter le développement de moyens d'intervention efficaces pour ces enfants afin de réduire l'impact de leur difficultés auditives sur leurs activités au quotidien.

8) Inconvénients et risques

Aucun risque n'est associé aux tâches que vous devrez accomplir ni aux mesures que nous recueillerons. Cependant, votre participation aux évaluations pourrait entraîner un certain état de stress ou de fatigue. Aussi, la pose du bonnet utilisé en électrophysiologie pourrait vous occasionner un certain inconfort (possibilité d'irritations lors de la préparation du cuir chevelu pour l'installation des électrodes). De courtes pauses sont

prévues pour contrer la fatigue et la baisse de motivation. Des pauses supplémentaires peuvent être prises au besoin.

9) Confidentialité

Tous les renseignements obtenus sur vous dans le cadre de cette recherche seront confidentiels, à moins d'une autorisation de votre part ou d'une exception de la loi tel qu'indiqué dans la *Loi sur la protection de la jeunesse* où des renseignements confidentiels peuvent être communiqués s'il existe un motif raisonnable de croire qu'un risque sérieux de mort ou de blessures graves menace une personne ou un groupe de personnes identifiable et que la nature de la menace inspire un sentiment d'urgence (article 72.8 - *Loi sur la protection de la jeunesse*). Nous allons remplacer votre nom par un code. Les dossiers seront conservés sous clef dans une filière au laboratoire de recherche de Benoît Jutras et les documents contenant vos coordonnées seront détruits cinq ans suivant la fin de cette étude ou suivant la publication des données reliées à l'étude. Quant aux données, elles seront conservées jusqu'à dix ans après leur publication. Les données codées seront partagées avec les co-chercheurs du projet de recherche à des fins d'analyses. De plus, afin de vérifier la saine gestion de la recherche, il est possible qu'un délégué du comité d'éthique de la recherche consulte les données de la recherche. Par ailleurs, les résultats de cette étude pourront être publiés ou communiqués dans des congrès scientifiques mais aucune information permettant de vous identifier ne sera alors dévoilée. À des fins de protection, le Ministère de la santé et des services sociaux pourrait avoir accès à votre nom et prénom, vos coordonnées, la date de début et de fin de votre participation au projet jusqu'à un an après la fin de ce projet.

10) Indemnité compensatoire

Une somme forfaitaire de 15$ sera remise en compensation des frais de déplacement, pour chacune des rencontres prévues pour ce projet de recherche.

11) Liberté de participation

Votre participation à l'étude est entièrement libre et volontaire. Vous pouvez refuser de participer à l'étude et vous pouvez annuler votre consentement en tout temps sans préjudice. Vos données ne seront pas utilisées et seront détruites advenant que vous décidez de vous retirer de l'étude.

12) Clause de responsabilité

En signant ce formulaire de consentement, vous ne renoncez à aucun de vos droits prévus par la loi. De plus, vous ne libérez pas les investigateurs de leur responsabilité légale et professionnelle advenant une situation qui vous causerait préjudice.

13) En cas de questions ou de difficultés

Pour plus d'informations concernant cette recherche, contactez le chercheur responsable (codirecteur de l'étudiante au doctorat) de cette étude au CHU Sainte-Justine, Benoît Jutras, (, l'étudiante au doctorat, Fauve Duquette-Laplante
ou la directrice de thèse, Amineh Koravand. Pour tout renseignement sur vos droits à titre de participant à ce projet de recherche, vous pouvez contacter le commissaire local aux plaintes et à la qualité des services du CHU Sainte-Justine au (514) 345-4749 ou le Bureau d'éthique et d'intégrité de la recherche de l'Université d'Ottawa (ethique@uottawa.ca) au (613) 562-5387.

Le traitement de l'information auditive d'enfants d'âge scolaire ayant subi un traumatisme crâniocérébral

14) Consentement

Consentement relatif à votre participation à l'étude

On m'a expliqué la nature et le déroulement du projet de recherche. J'ai pris connaissance du formulairede consentement et on m'en a remis un exemplaire. J'ai eu l'occasion de poser des questions auxquelleson a répondu. Après réflexion, j'accepte de participe à ce projet de recherche.

Nom du participant	Date de naissance
Signature du participant	Date

15) Formule d'engagement de la personne déléguée par le chercheur

J'ai expliqué au participant tous les aspects pertinents de la recherche et j'ai répondu aux questions qu'ils m'ont posées. Je leur ai indiqué que la participation au projet de recherche est libre et volontaire et que la participation peut être cessée en tout temps.

Nom de la personne qui a obtenu le consentement (lettres moulées)	Signature	Date

Le traitement de l'information auditive d'enfants d'âge scolaireayant subi un traumatisme crâniocérébral

FORMULAIRE D'INFORMATION ET DE CONSENTEMENT

1) Titre de l'étude

Le traitement de l'information auditive d'enfants d'âge scolaire ayant subi un traumatisme crâniocérébral léger

2) Nom des chercheurs

Benoît Jutras, Ph.D., Chercheur, Centre de recherche, CHU Sainte-Justine; Professeur titulaire, Écoled'orthophonie et d'audiologie, Université de Montréal
Fauve Duquette-Laplante, M.H.Sc., Audiologiste, Étudiante au doctorat, Sciences biomédicales, option audiologie, Université de Montréal et Sciences de la réadaptation, Université d'Ottawa
Amineh Koravand, Ph.D., Professeure agrégée, Programme d'audiologie et d'orthophonie de l'Université d'Ottawa**Miriam Beauchamp, Ph.D.,** Chercheure**,** Centre de recherche, CHU Sainte-Justine; Professeure agrégée, Département de psychologie, Université de Montréal
Jocelyn Gravel, M.D., Pédiatre urgentologue, CHU Sainte-Justine; Professeur agrégé de clinique, Département depédiatrie, Université de Montréal
Justine Ratelle, M.P.A., Audiologiste, CHU Sainte-Justine

3) Organisme subventionnaire

Concours Trauma 2019-2020, CHU Sainte-Justine

4) Invitation à participer à un projet de recherche

Des membres de l'équipe de recherche en audiologie et en neurotraumatologie du CHU Sainte-Justine et de l'Université d'Ottawa veulent documenter les capacités auditives d'enfants ayant subi un traumatisme crâniocérébralléger (TCC-L), dans le cadre de la thèse de l'étudiante au doctorat, Fauve Duquette-Laplante. On en connaît peu surles difficultés auditives que peuvent vivre des enfants ayant subi un TCC-L et leurs impacts au quotidien. Il apparaîtdonc important de déterminer les dysfonctions auditives de ces enfants afin d'intervenir le plus rapidement possible et de façon appropriée pour réduire ces impacts. Nous vous invitons à lire ce formulaire d'information afin de décidersi vous êtes intéressé à ce que votre enfant participe à cette étude. Nous encourageons les parents à inclure leur enfantdans la discussion et la prise de décision dans la mesure où l'enfant peut comprendre.

5) Nature de ce projet

Le traumatisme crâniocérébral léger (TCC-L) est une blessure fréquente chez les enfants. Il peut laisser, entre autres, des séquelles comme une perte auditive. Toutefois, d'autres symptômes auditifs sont rarement évalués, principalementceux reliés aux capacités auditives de haut niveau faisant appel au fonctionnement de la partie neurale du système auditif (du tronc cérébral jusqu'au cerveau, appelé système auditif central). Il est possible d'évaluer ces symptômes à l'aide de mesures de l'activité du cerveau qui vérifie l'intégrité des structures du système auditif. La présente étude pilote vise à développer un protocole qui utilise ces mesures afin de déterminer comment des signaux auditifs sont traités par le cerveau lorsqu'ils sont présentés dans le silence et quand ils le sont dans le bruit. Les résultats de cette étude pilote serviront de guide pour poursuivre la recherche auprès d'enfants ayant eu un TTC-L. Quinze adultes et quinze enfants qui n'ont pas eu de blessure à la tête et qui n'ont pas non plus de problèmes auditifs soupçonnés participeront à ce projet pilote et votre enfant en fera partie s'il remplit les critères d'admissibilité.

Le traitement de l'information auditive d'enfants d'âge scolaireayant subi un traumatisme crâniocérébral

6) Déroulement

Mesures. Si votre enfant est admissible à la recherche, il aura une évaluation de son audition et une mesure de l'activité cérébrale, appelée électrophysiologie. Ces évaluations s'échelonneront sur une rencontre d'une durée totalede deux heures trente minutes, incluant des pauses. Toutefois, selon l'âge de votre enfant et de sa capacité d'écoute et de concentration, une rencontre supplémentaire pourrait avoir lieu. Ces rencontres seront prévues selon vos disponibilités et celles de votre enfant et se dérouleront à l'École d'orthophonie et en audiologie de l'Université de Montréal.

Évaluation de l'audition

Une évaluation de l'audition sera effectuée. Votre enfant sera assis dans une cabine où le niveau de bruit ambiant estcontrôlé, appelée cabine insonore. À l'aide d'écouteurs, nous présenterons des sons pour déterminer ses seuils d'audition. Nous vérifierons aussi comment ses tympans bougent à l'aide d'une légère pression envoyée dans le conduit auditif. Nous lui demanderons également de répéter des séries de mots présentés individuellement. Cette partie prendra environ trente minutes. Les résultats à ces tests doivent être normaux afin de poursuivre sa participationà la présente étude.

Mesure de l'activité du cerveau (électrophysiologie)

Durant cette mesure, votre enfant sera assis confortablement et on placera un bonnet sur sa tête. Ce bonnet comportedes petits capteurs métalliques (électrodes) qui seront en contact avec le cuir chevelu. Ces capteurs servent à mesurer l'activité électrique du cerveau mais n'influenceront d'aucune façonle fonctionnement du cerveau de votre enfant. Il n'y a pas de douleur associée à la pose du bonnet. Tout au plus, votre enfant pourrait être incommodé par le temps nécessaire à l'installation et par une légère sensation d'irritation du cuir chevelu lors de la préparation à la pose des électrodes. Il faut frotter le cuir chevelu avec un gel pour que les électrodes du bonnet

captent plus facilement les ondes du cerveau. Quatre capteurs avec du gel seront aussi installés autour des yeux de votre enfant. À la suite de l'installation du casque, des écouteurs seront placés dans le conduit de chaque oreille et serviront à présenter des sons. Votre enfant n'aura qu'à rester calme et éveillé durant cette évaluation. Il regardera unfilm de son choix, avec des sous-titres, sans son et n'aura pas à répondre ni à porter attention aux sons. Cette évaluation prendra environ deux heures, dont 45 minutes dédiées à la pose du casque.

7) Avantages et bénéfices

Votre enfant bénéficiera d'une évaluation de son audition. Les résultats vous seront transmis oralement. Dans le casde résultats anormaux, des références vous seront données si le problème n'est pas connu de votre part. Dans le futur,pour l'ensemble des enfants aux prises avec un TCC-L, les retombées attendues incluent une meilleure connaissancede leurs difficultés. Les résultats pourraient éventuellement orienter le développement de moyens d'intervention efficaces pour ces enfants afin de réduire l'impact de leur difficultés auditives sur leurs activités au quotidien.

8) Inconvénients et risques

Aucun risque n'est associé aux tâches que devra accomplir votre enfant ni aux mesures que nous recueillerons. Cependant, la participation de votre enfant aux évaluations pourrait entraîner un certain état de stress ou de fatigue. Aussi, la pose du bonnet utilisé en électrophysiologie pourrait lui occasionner un certain inconfort (possibilité d'irritations lors de la préparation du cuir chevelu pour l'installation des électrodes). De courtes pauses sont prévues

pour contrer la fatigue et la baisse de motivation. Des pauses supplémentaires peuvent être prises au besoin.

9) Confidentialité

Tous les renseignements obtenus sur votre enfant dans le cadre de cette recherche seront confidentiels, à moins d'uneautorisation de votre part ou d'une exception de la loi tel qu'indiqué dans la *Loi sur la protection de la jeunesse* où des renseignements confidentiels peuvent être communiqués s'il existe un motif raisonnable de croire qu'un risque sérieux de mort ou de blessures graves menace une personne ou un groupe de personnes identifiable et que la naturede la menace inspire un sentiment d'urgence (article 72.8 - *Loi sur la protection de la jeunesse*). Nous allons remplacer son nom par un code. Les dossiers seront conservés sous clef dans une filière au laboratoire de recherche de Benoît Jutras et les documents contenant vos coordonnées ou celles de votre enfant seront détruits cinq ans suivant la fin de cette étude ou suivant la publication des données reliées à l'étude. Quant aux données, elles seront conservées jusqu'à dix ans après leur publication. Les données codées seront partagées avec les co-chercheurs du projet de recherche à des fins d'analyses. De plus, afin de vérifier la saine gestion de la recherche, il est possible qu'un délégué du comité d'éthique de la recherche consulte les données de la recherche. Par ailleurs, les résultats de cette étude pourront être publiés ou communiqués dans des congrès scientifiques mais aucune information permettant d'identifier votre enfant ne sera alors dévoilée. À des fins de protection, le Ministère de la santé et des services sociaux pourrait avoir accès à votre nom et prénom ainsi que ceux de votre enfant, ses coordonnées, la date de début et de fin de sa participation au projet jusqu'à un an après la fin de ce projet.

10) Indemnité compensatoire

Une somme forfaitaire de 15$ sera remise en compensation des frais de déplacement, pour chacune des rencontres prévues pour ce projet de recherche.

11) Liberté de participation

La participation de votre enfant à l'étude est entièrement libre et volontaire. Vous et votre enfant pouvez refuserde participer à l'étude et vous pouvez annuler votre consentement en tout temps sans préjudice. Vos données ne seront pas utilisées et seront détruites advenant que vous décidez de vous retirer de l'étude.

12) Clause de responsabilité

En signant ce formulaire de consentement, vous ne renoncez à aucun de vos droits prévus par la loi ni à ceux de votre enfant. De plus, vous ne libérez pas les investigateurs de leur responsabilité légale et professionnelle advenant une situation qui causerait préjudice à votre enfant.

13) En cas de questions ou de difficultés

Pour plus d'informations concernant cette recherche, contactez le chercheur responsable (codirecteur de l'étudiante au doctorat) de cette étude au CHU Sainte-Justine, Benoît Jutras, l'étudiante au doctorat, Fauve Duquette-Laplante ou la directrice de thèse, Amineh Koravand. Pour tout renseignement sur vos droits à titre de participant à ce projet de recherche, vous pouvez contacterle commissaire local aux plaintes et à la qualité des services du CHU Sainte-Justine au (514) 345-4749 ou le Bureaud'éthique et d'intégrité de la recherche de l'Université d'Ottawa (ethique@uottawa.ca) au (613) 562-5387.

Le traitement de l'information auditive d'enfants d'âge scolaireayant subi un traumatisme crâniocérébral

14) Consentement et Assentiment

a. Consentement du parent relatif à la participation de son enfant à l'étude

On m'a expliqué la nature et le déroulement du projet de recherche. J'ai pris connaissance du formulaire de consentement et on m'en a remis un exemplaire. J'ai eu l'occasion de poser des questions auxquelles on a répondu. Après réflexion, j'accepte que mon enfant participe à ce projet de recherche.

Nom de l'enfant	Date de naissance	
Nom du parent/tuteur	Signature du parent/tuteur	Date

b. Assentiment de l'enfant à participer à l'étude

On m'a expliqué le projet de recherche et j'accepte d'y participer.

(Signature de l'enfant)	Date

15) Formule d'engagement de la personne déléguée par le chercheur

J'ai expliqué au participant ou à son parent/tuteur ou aux deux à la fois tous les aspects pertinents de la recherche et j'airépondu aux questions qu'ils m'ont posées. Je leur ai indiqué que la participation au projet de recherche est libre et volontaire et que la participation peut être cessée en tout temps.

Nom de la personne qui a obtenu le consentement (lettres moulées)	Signature	Date

Le traitement de l'information auditive d'enfants d'âge scolaireayant subi un traumatisme crâniocérébral léger

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FORMULAIRE D'INFORMATION ET DE CONSENTEMENT

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1) Titre de l'étude

Le traitement de l'information auditive d'enfants d'âge scolaire ayant subi un traumatisme crâniocérébral léger

2) Nom des chercheurs

Benoît Jutras, Ph.D., Chercheur, Centre de recherche, CHU Sainte-Justine; Professeur titulaire, École d'orthophonie et d'audiologie, Université de Montréal
Fauve Duquette-Laplante, M.H.Sc., Audiologiste, Étudiante au doctorat, Sciences biomédicales, option audiologie, Université de Montréal et Sciences de la réadaptation, Université d'Ottawa
Amineh Koravand, Ph.D., Professeure agrégée, Programme d'audiologie et d'orthophonie de l'Universitéd'Ottawa
Miriam Beauchamp, Ph.D., Chercheure**,** Centre de recherche, CHU Sainte-Justine; Professeure agrégée, Département de psychologie, Université de Montréal
Jocelyn Gravel, M.D., Pédiatre urgentologue, CHU Sainte-Justine; Professeur agrégé de clinique, Département de pédiatrie, Université de Montréal
Justine Ratelle, M.P.A., Audiologiste, CHU Sainte-Justine
Isabelle Gagnon, PhD, Chercheure, Institut de recherche du CUSM, Hôpital de Montréal pour enfants; Professeure titulaire, School of Physical and Occupational Therapy, Medicine and Health Sciences, McGill University

3) Organisme subventionnaire

Concours Trauma 2019-2020, CHU Sainte-Justine

4) Invitation à participer à un projet de recherche

Des membres de l'équipe de recherche en audiologie et en neurotraumatologie du CHU Sainte-Justine, de l'Université d'Ottawa et l'Hôpital de Montréal pour enfants – CUSM veulent documenter les capacités auditives d'enfants ayant subi un traumatisme crâniocérébral léger (TCC-L), dans le cadre de la thèse de l'étudiante au doctorat, Fauve Duquette-Laplante. On en connaît peu sur les difficultés auditives que peuvent vivre des enfants ayant subi un TCC-L et leurs impacts au quotidien. Il apparaît donc important de déterminer les dysfonctions auditives de ces enfants afin d'intervenir le plus rapidement possible et de façon appropriée pour réduire ces impacts. Nous vous invitons à lire ce formulaire d'information afin de décider si vous êtes intéressé à ce que votre enfant participe à cette étude. Nous encourageons les parents à inclure leur enfant dans la discussion et la prise de décision dans la mesure où l'enfant peut comprendre.

5) Nature de ce projet

Le traumatisme crâniocérébral léger (TCC-L) est une blessure fréquente chez les enfants. Il peut laisser, entre autres, des séquelles, comme une perte auditive. Toutefois, d'autres symptômes auditifs sont rarement évalués, principalement ceux reliés aux capacités auditives de haut niveau faisant appel au fonctionnement de la partie neurale du système auditif (du tronc cérébral jusqu'au cerveau, appelé système auditif central). La présente étude vise à examiner ces capacités auditives de haut niveau, nommées capacités de traitement auditif central, d'enfants de huit à douze ans ayant subi un TCC-L. L'étude comprendra deux groupes d'enfants, ceux ayant subi un TCC-L (groupe expérimental) et ceux qui n'en n'ont pas subi et qui n'ont pas non plus de problèmes auditifs soupçonnés

(groupe contrôle). Votre enfant fait partie du groupe expérimental. Soixante enfants participeront à ce projet dont la moitié feront partie du groupe expérimental.

6) Déroulement

Mesures. Si votre enfant est admissible à la recherche, il aura une évaluation audiologique, une évaluation de son attention et de sa mémoire et une mesure de l'activité cérébrale, appelée électrophysiologie. Ces évaluations s'échelonneront sur une ou deux rencontres d'une durée totale d'environ cinq heures, incluant des pauses. Toutefois, selon l'âge de votre enfant et de sa capacité d'écoute et de concentration, une rencontre supplémentaire pourrait avoir lieu. Ces rencontres seront prévues selon vos disponibilités et celles de votre enfant et se dérouleront à l'École d'orthophonie et en audiologie de l'Université de Montréal. Vous aurez aussi à remplir des questionnaires.

Évaluation de l'audition

Avant de procéder à une évaluation de l'audition de votre enfant, vous ainsi que votre enfant aurez à répondre à des questions spécifiques à son audition, comme la présence d'otites, sur sa sensibilité à l'écoute de sons ou à la présence de bruit dans ses oreilles. Ensuite, pour l'évaluation de l'audition, votre enfant sera assis dans une cabine où le niveau de bruit ambiant est contrôlé, appelée cabine insonore. À l'aide d'écouteurs, nous présenterons des sons pour déterminer ses seuils d'audition. De plus, nous lui présenterons des sons ou des mots dans chaque oreille dont le niveau augmentera afin de vérifier le niveau où votre enfant peut tolérer ces sons. Nous vérifierons aussi comment ses tympans bougent à l'aide d'une sonde placée dans le premier tiers du conduit de l'oreille qui enverra une légère pression dans le conduit auditif. À l'aide de la même sonde et d'un écouteur placé dans ou sur l'oreille, votre enfant entendra des sons forts dans chaque oreille, envoyés à un niveau sécuritaire, pour faire contracter un petit muscle situé dans l'oreille. La contraction du muscle protège l'oreille contre les sons forts. Pour un autre test, nous placerons une sonde sur le bord du conduit de l'oreille et votre enfant entendra des sons présentés à un niveau qui n'est ni trop fort, ni trop faible. Pour ces deux tests, votre enfant n'aura rien à faire et il devra éviter de bouger. Nous lui demanderons de répéter des séries de mots présentés individuellement. Cette partie prendra environ 45 minutes. Les résultats à ces tests doivent être normaux afin de poursuivre sa participation à la présente étude.

Évaluation des capacités de traitement auditif central

S'il est admisible, votre enfant effectuera six épreuves auditives de haut niveau. Elles seront faites sous écouteurs, dans une cabine insonore. Les épreuves auditives consistent à répéter des chiffres présentés en même temps aux deux oreilles; les chiffres étant différents dans chaque oreille, à répéter des mots, des chiffres ou des phrases présentés en présence de bruit, à identifier des sons dans un bruit, à détecter la présence d'un court silence dans des sons et à répéter des séquences de sons dont leur durée ou fréquence varie. Cette évaluation prendra environ deux heures trente minutes incluant des pauses au besoin.

Évaluation de certaines fonctions cognitives

Des épreuves cognitives seront effectuées auprès de votre enfant. Les capacités d'attention de votre enfant seront mesurés à l'aide de tests informatisés. Ces tests mesureront sa capacité à porter attention à une cible visuelle ou auditive (ex : compter des sons ou des images), à faire deux tâches en même temps, à garder en mémoire des informations à court terme et à inhiber une action (ex : réagir seulement à certains sons et en ignorer d'autres). Votre enfant sera assis près d'un ordinateur et devra répondre à partir de touches d'un clavier. Cette évaluation prendra environ 30 minutes.

Questionnaires

Vous et votre enfant devrez répondre à des questions à différents moments durant l'étude. Dans un premier

temps, pour déterminer si votre enfant est admissible à l'étude, l'infirmière de recherche vous posera des questions lors votre visite à l'urgence. Dans un deuxième temps, si votre enfant est admissible, vous devrez ainsique votre enfant remplir un questionnaire portant sur les comportements d'écoute de votre enfant à l'école ou à la maison. Ces questionnaires vous seront acheminés avant la première rencontre d'évaluation et nous estimons que chaque questionnaire peut être rempli en 15 minutes. Avec votre autorisation, nous solliciterons aussi la participation de l'enseignant de votre enfant pour compléter un questionnaire sur ses comportements d'écoute à l'école. De plus, vous et votre enfant aurez à remplir un questionnaire sur des symptômes apparus à la suite du TCC-L à trois reprises : à votre visite à l'urgence, lors de la première évaluation et lors de la seconde évaluation. Ces questionnaires prendront environ 10 minutes à remplir. Finalement, lors de la première et de la seconde évaluation, vous aurez aussi à remplir un autre questionnaire concernant l'attention que votre enfant porte à des actions de la vie courante et des gestes impulsifs qu'il pourrait parfois poser. Ce questionnaire devrait prendre aussi 10 minutes à remplir. Avec votre autorisation, nous solliciterons aussi la participation de l'enseignant de votre enfant pour compléter un questionnaire sur ses comportements d'écoute à l'école.

Mesure de l'activité du cerveau (électrophysiologie)

Durant cette mesure, votre enfant sera assis confortablement et on placera un bonnet sur sa tête. Ce bonnet comporte des petits capteurs métalliques (électrodes) qui seront en contact avec le cuir chevelu. Ces capteurs servent à mesurer l'activité électrique du cerveau mais n'influenceront d'aucune façon le fonctionnement du cerveau de votre enfant. Il n'y a pas de douleur associée à la pose du bonnet. Tout au plus, votre enfant pourrait être incommodé par le temps nécessaire à l'installation et par une légère sensation d'irritation du cuir chevelu lors de la préparation à la pose des électrodes. Il faut frotter le cuir chevelu avec un gel pour que les électrodes du bonnet captent plus facilement les ondes du cerveau. Quatre capteurs avec du gel seront aussi installés autour des yeux de votre enfant. À la suite de l'installation du casque, des écouteurs seront placés dans le conduit de chaque oreille et serviront à présenter des sons. Votre enfant n'aura qu'à rester calme et éveillé durant cette évaluation. Il regardera un film de son choix, avec des sous-titres, sans son et n'aura pas à répondre ni à porter attention aux sons. Cette évaluation prendra environ une heure trente minutes, dont 45 minutes dédiées à la pose du casque.

7) Avantages et bénéfices

Votre enfant bénéficiera d'une évaluation de son audition, des capacités auditives de haut niveau ainsi que de ses capacités d'attention, d'inhibition et de mémoire à court terme. Les résultats vous seront transmis oralement. Dans le cas de résultats anormaux, des références vous seront données si le problème n'est pas connu de votre part. Dans le futur, pour l'ensemble des enfants aux prises avec un TCC-L, les retombées attendues incluent une meilleure connaissance de leurs difficultés. Les résultats pourraient éventuellement orienter le développement de moyens d'intervention efficaces pour ces enfants afin de réduire l'impact de leur difficultés auditives sur leurs activités au quotidien.

8) Inconvénients et risques

Aucun risque n'est associé aux tâches que devra accomplir votre enfant ni aux mesures que nous recueillerons. Cependant, la participation de votre enfant aux évaluations pourrait entraîner un certain état de stress ou de fatigue. Aussi, la pose du bonnet utilisé en électrophysiologie pourrait lui occasionner un certain inconfort (possibilité d'irritations lors de la préparation du cuir chevelu pour l'installation des électrodes). De courtes pauses sont prévues pour contrer la fatigue et la baisse de motivation. Des pauses supplémentaires peuvent être prises au besoin.

9) Confidentialité

Tous les renseignements obtenus sur votre enfant dans le cadre de cette recherche seront confidentiels, à moins d'une autorisation de votre part ou d'une exception de la loi tel qu'indiqué dans la *Loi sur la protection de la jeunesse* où des renseignements confidentiels peuvent être communiqués s'il existe un motif raisonnable de croire qu'un risque sérieux de mort ou de blessures graves menace une personne ou un groupe de personnes identifiable et que la nature de la menace inspire un sentiment d'urgence (article 72.8 - *Loi sur la protection de la jeunesse*). Nous allons remplacer son nom par un code. Les dossiers seront conservés sous clef dans une filière au laboratoire de recherche de Benoît Jutras et les documents contenant vos coordonnées ou celles de votre enfant seront détruits cinq ans suivant la fin de cette étude ou suivant la publication des données reliées à l'étude. Quantaux données, elles seront conservées jusqu'à dix ans après leur publication. Les données codées seront partagéesavec les co-chercheurs du projet de recherche à des fins d'analyses. De plus, afin de vérifier la saine gestion de larecherche, il est possible qu'un délégué du comité d'éthique de la recherche consulte les données de la recherche. Par ailleurs, les résultats de cette étude pourront être publiés ou communiqués dans des congrès scientifiques mais aucune information permettant d'identifier votre enfant ne sera alors dévoilée. À des fins de protection, le Ministère de la santé et des services sociaux pourrait avoir accès à votre nom et prénom ainsi que ceux de votre enfant, ses coordonnées, la date de début et de fin de sa participation au projet jusqu'à un an après la fin de ce projet.

10) Indemnité compensatoire

Une somme forfaitaire de 15$ sera remise en compensation des frais de déplacement, pour chacune des rencontres prévues pour ce projet de recherche.

11) Liberté de participation

La participation de votre enfant à l'étude est entièrement libre et volontaire. Vous et votre enfant pouvez refuser de participer à l'étude et vous pouvez annuler votre consentement en tout temps, cela n'affectera pas la qualité des soins qui vous seront offerts. Vos données ne seront pas utilisées et seront détruites advenant que vous décidez de vous retirer de l'étude.

12) Clause de responsabilité

En signant ce formulaire de consentement, vous ne renoncez à aucun de vos droits prévus par la loi ni à ceux de votre enfant. De plus, vous ne libérez pas les investigateurs de leur responsabilité légale et professionnelle advenant une situation qui causerait préjudice à votre enfant.

13) En cas de questions ou de difficultés

Pour plus d'informations concernant cette recherche, contactez le chercheur responsable (codirecteur de l'étudiante au doctorat) de cette étude au CHU Sainte-Justine, Benoît Jutras
, l'étudiante au doctorat, Fauve Duquette-Laplante ou la directrice de thèse, Amineh Koravand. Pour l'Hôpital de Montréal pour enfants – CUSM, veuillez contacter la chercheure responsable Isabelle Gagnon Pour tout renseignement sur vos droits à titre de participant à ce projet de recherche, vous pouvez contacter le commissaire local aux plaintes et à la qualité des services du CHU Sainte-Justine au (514) 345-4749, de l'Hôpital de Montréal pour enfants – CUSM : (514) 412-4400 poste 22223,ou le Bureau d'éthique et d'intégrité de la recherche de l'Université d'Ottawa (ethique@uottawa.ca) au (613) 562-5387.

14) Consentement et Assentiment

a. Consentement du parent relatif à la participation de son enfant à l'étude

On m'a expliqué la nature et le déroulement du projet de recherche. J'ai pris connaissance du formulaire de consentement et on m'en a remis un exemplaire. J'ai eu l'occasion de poser des questions auxquelles on a répondu. Après réflexion, j'accepte que mon enfant participe à ce projet de recherche.

Nom de l'enfant	Date de naissance	
Nom du parent/tuteur	Signature du parent/tuteur	Date

b. Consentement du parent à participer à la recherche

On m'a expliqué la nature et le déroulement du projet de recherche. J'ai pris connaissance du formulaire de consentement et on m'en a remis un exemplaire. J'ai eu l'occasion de poser des questions auxquelles on a répondu. Après réflexion, j'accepte de compléter les questionnaires.

Nom du parent/tuteur	Signature du parent/tuteur	Date

c. Assentiment de l'enfant à participer à l'étude

On m'a expliqué le projet de recherche et j'accepte d'y participer.

(Signature de l'enfant)	Date

d. Consentement du parent relatif au contact de l'enseignant

On m'a expliqué la nature et le déroulement du projet de recherche. J'ai eu l'occasion de poser des questions auxquelles on a répondu. Après réflexion, j'accepte que l'équipe de recherche contacte l'enseignant de mon enfant afin qu'il donne des informations sur mon enfant à partir du questionnaire « *Échelle des comportements auditifs* ».

Nom de l'enseignant-e:_____ École : _____
Téléphone/courriel :_____

15) Formule d'engagement de la personne déléguée par le chercheur

J'ai expliqué au participant ou à son parent/tuteur ou aux deux à la fois tous les aspects pertinents de la recherche et j'ai répondu aux questions qu'ils m'ont posées. Je leur ai indiqué que la participation au projet de recherche est libre et volontaire et que la participation peut être cessée en tout temps.

Nom de la personne qui a obtenu le consentement (lettres moulées)	Signature	Date

Le traitement de l'information auditive d'enfants d'âge scolaireayant subi un traumatisme crâniocérébral

16) Autorisation pour l'obtention de dossiers professionnels

Par la présente, j'autorise l'équipe de recherche impliquée dans le projet « *Le traitement de l'information auditived'enfants d'âge scolaire ayant subi un traumatisme crâniocérébral léger »* à recevoir de votre établissement une copie des rapports suivants concernant mon enfant :

Documents et rapports relatifs au diagnostic de TCC-L

Nom de l'établissement où l'enfant a reçu des services

Nom de l'enfant (lettres moulées) _____ Date de naissance _____

Nom du parent ou tuteur (lettres moulées) _____

Signature du parent ou tuteur _____ Date _____

Nom du chercheur ou délégué (lettres moulées) _____

Signature du chercheur ou délégué _____ Date _____

17) Interprète

a. Interprète utilisé? Oui ☐ Non ☐ S.O. ☐

Si un interprète a été utilisé, langue d'interprétation : _____

Nom de l'interprète _____ Signature de l'interprète _____ Date _____

Remettre les documents à : Fauve Duquette-Laplante, M.H.Sc
fauve.duquette-laplante@umontreal.ca
Téléphone : 514-343-6111 poste 30952

Université de Montréal

CHU Sainte-Justine
Le centre hospitalier universitaire mère-enfant
Université de Montréal

Centre universitaire de santé McGill
McGill University Health Centre

uOttawa

Le traitement de l'information auditive d'enfants d'âge scolaireayant subi un traumatisme crâniocérébral

FORMULAIRE D'INFORMATION ET DE CONSENTEMENT

1) Titre de l'étude

Le traitement de l'information auditive d'enfants d'âge scolaire ayant subi un traumatisme crâniocérébral léger

2) Nom des chercheurs

Benoît Jutras, Ph.D., Chercheur, Centre de recherche, CHU Sainte-Justine; Professeur titulaire, École d'orthophonie et d'audiologie, Université de Montréal
Fauve Duquette-Laplante, M.H.Sc., Audiologiste, Étudiante au doctorat, Sciences biomédicales, option audiologie, Université de Montréal et Sciences de la réadaptation, Université d'Ottawa
Amineh Koravand, Ph.D., Professeure agrégée, Programme d'audiologie et d'orthophonie de l'Universitéd'Ottawa
Miriam Beauchamp, Ph.D., Chercheure**,** Centre de recherche, CHU Sainte-Justine; Professeure agrégée, Département de psychologie, Université de Montréal
Jocelyn Gravel, M.D., Pédiatre urgentologue, CHU Sainte-Justine; Professeur agrégé de clinique, Département de pédiatrie, Université de Montréal
Justine Ratelle, M.P.A., Audiologiste, CHU Sainte-Justine
Isabelle Gagnon, PhD, Chercheure, Institut de recherche du CUSM, Hôpital de Montréal pour enfants; Professeure titulaire, School of Physical and Occupational Therapy, Medicine and Health Sciences, McGill University

3) Organisme subventionnaire

Concours Trauma 2019-2020, CHU Sainte-Justine

4) Invitation à participer à un projet de recherche

Des membres de l'équipe de recherche en audiologie et en neurotraumatologie du CHU Sainte-Justine, de l'Université d'Ottawa et l'Hôpital de Montréal pour enfants – CUSM veulent documenter les capacités auditives d'enfants ayant subi un traumatisme crâniocérébral léger (TCC-L), dans le cadre de la thèse de l'étudiante au doctorat, Fauve Duquette-Laplante. On en connaît peu sur les difficultés auditives que peuvent vivre des enfants ayant subi un TCC-L et leurs impacts au quotidien. Il apparaît donc important de déterminer les dysfonctions auditives de ces enfants afin d'intervenir le plus rapidement possible et de façon appropriée pour réduire ces impacts. Nous vous invitons à lire ce formulaire d'information afin de décider si vous êtes intéressé à ce que votre enfant participe à cette étude. Nous encourageons les parents à inclure leur enfant dans la discussion et la prise de décision dans la mesure où l'enfant peut comprendre.

5) Nature de ce projet

Le traumatisme crâniocérébral léger (TCC-L) est une blessure fréquente chez les enfants. Il peut laisser, entre autres, des séquelles comme une perte auditive. Toutefois, d'autres symptômes auditifs sont rarement évalués, principalement ceux reliés aux capacités auditives de haut niveau faisant appel au fonctionnement de la partie neurale du système auditif (du tronc cérébral jusqu'au cerveau, appelé système auditif central). La présente étude vise à examiner ces capacités auditives de haut niveau, nommées capacités de traitement auditif central, d'enfants de huit à douze ans ayant subi un TCC-L. L'étude comprendra deux groupes d'enfants, ceux ayant subi un TCC-L (groupe expérimental) et ceux qui n'en n'ont pas subi et qui n'ont pas non plus de problèmes auditifs soupçonnés (groupe contrôle). Votre enfant fait partie du groupe contrôle. Soixante enfants

participeront à ce projet dont la moitié feront partie du groupe contrôle.

6) Déroulement

Mesures. Si votre enfant est admissible à la recherche, il aura une évaluation audiologique, une évaluation de son attention et de sa mémoire et une mesure de l'activité cérébrale, appelée électrophysiologie. Ces évaluations s'échelonneront sur une ou deux rencontres d'une durée totale d'environ cinq heures, incluant des pauses. Toutefois, selon l'âge de votre enfant et de sa capacité d'écoute et de concentration, une rencontre supplémentaire pourrait avoir lieu. Ces rencontres seront prévues selon vos disponibilités et celles de votre enfant et se dérouleront à l'École d'orthophonie et en audiologie de l'Université de Montréal. Vous aurez aussi à remplir des questionnaires. Ces mesures seront effetuées de nouveau trois mois plus tard.

Évaluation de l'audition

Avant de procéder à une évaluation de l'audition de votre enfant, vous ainsi que votre enfant aurez à répondre à des questions spécifiques à son audition, comme la présence d'otites, sur sa sensibilité à l'écoute de sons ou à la présence de bruit dans ses oreilles. Ensuite, pour l'évaluation de l'audition, votre enfant sera assis dans une cabine où le niveau de bruit ambiant est contrôlé, appelée cabine insonore. À l'aide d'écouteurs, nous présenterons des sons pour déterminer ses seuils d'audition. De plus, nous lui présenterons des sons ou des mots dans chaque oreille dont le niveau augmentera afin de vérifier le niveau où votre enfant peut tolérer ces sons. Nous vérifierons aussi comment ses tympans bougent à l'aide d'une sonde placée dans le premier tiers du conduit de l'oreille qui enverra une légère pression dans le conduit auditif. À l'aide de la même sonde et d'un écouteur placé dans ou sur l'oreille, votre enfant entendra des sons forts dans chaque oreille, envoyés à un niveau sécuritaire, pour faire contracter un petit muscle situé dans l'oreille. La contraction du muscle protège l'oreille contre les sons forts. Pour un autre test, nous placerons une sonde sur le bord du conduit de l'oreille et votre enfant entendra des sons présentés à un niveau qui n'est ni trop fort, ni trop faible. Pour ces deux tests, votre enfant n'aura rien à faire et il devra éviter de bouger. Nous lui demanderons de répéter des séries de mots présentés individuellement. Cette partie prendra environ 45 minutes. Les résultats à ces tests doivent être normaux afin de poursuivre sa participation à la présente étude.

Évaluation des capacités de traitement auditif central

S'il est admisible, votre enfant effectuera six épreuves auditives de haut niveau. Elles seront faites sous écouteurs, dans une cabine insonore. Les épreuves auditives consistent à répéter des chiffres présentés en même temps aux deux oreilles; les chiffres étant différents dans chaque oreille, à répéter des mots, des chiffres ou des phrases présentés en présence de bruit, à identifier des sons dans un bruit, à détecter la présence d'un court silence dans des sons et à répéter des séquences de sons dont leur durée ou fréquence varie. Cette évaluation prendra environ deux heures trente minutes incluant des pauses au besoin.

Évaluation de certaines fonctions cognitives

Des épreuves cognitives standardisées seront effectuées auprès de votre enfant. Les capacités d'attention de votre enfant seront mesurés à l'aide de tests papier-crayon fréquemment utilisés en psychologie. Ces tests mesureront sa capacité à porter attention à une cible visuelle ou auditive (ex : compter des sons ou des images), à faire deux tâches en même temps, à garder en mémoire des informations à court terme et à inhiber une action (ex : réagir seulement à certains sons et en ignorer d'autres). Cette évaluation prendra environ une heure.

Questionnaires

Vous devrez ainsi que votre enfant remplir un questionnaire portant sur les comportements d'écoute de votre enfant à l'école ou à la maison. Vous aurez aussi à remplir un autre questionnaire concernant l'attention que votre enfant porte à des actions de la vie courante et des gestes impulsifs qu'il pourrait parfois poser. Ces questionnaires vous seront acheminés avant la première rencontre d'évaluation et nous estimons qu'ils pourront être remplis en environ 10 à 15 minutes chacun. Vous aurez à le faire également lors de la deuxième évaluation. Avec votre autorisation, nous solliciterons aussi la participation de l'enseignant de votre enfant pour compléter un questionnaire sur ses comportements d'écoute à l'école.

Mesure de l'activité du cerveau (électrophysiologie)

Durant cette mesure, votre enfant sera assis confortablement et on placera un bonnet sur sa tête. Ce bonnet comporte des petits capteurs métalliques (électrodes) qui seront en contact avec le cuir chevelu. Ces capteurs servent à mesurer l'activité électrique du cerveau mais n'influenceront d'aucune façon le fonctionnement du cerveau de votre enfant. Il n'y a pas de douleur associée à la pose du bonnet. Tout au plus, votre enfant pourrait être incommodé par le temps nécessaire à l'installation et par une légère sensation d'irritation du cuir chevelu lors de la préparation à la pose des électrodes. Il faut frotter le cuir chevelu avec un gel pour que les électrodes du bonnet captent plus facilement les ondes du cerveau. Quatre capteurs avec du gel seront aussi installés autour des yeux de votre enfant. À la suite de l'installation du casque, des écouteurs seront placés dans le conduit de chaque oreille et serviront à présenter des sons. Votre enfant n'aura qu'à rester calme et éveillé durant cette évaluation. Il regardera un film de son choix, avec des sous-titres, sans son et n'aura pas à répondre ni à porter attention aux sons. Cette évaluation prendra environ une heure trente minutes, dont 45 minutes dédiées à la pose du casque.

7) Avantages et bénéfices

Votre enfant bénéficiera d'une évaluation de son audition, des capacités auditives de haut niveau ainsi que de ses capacités d'attention, d'inhibition et de mémoire à court terme. Les résultats vous seront transmis oralement. Dans le cas de résultats anormaux, des références vous seront données si le problème n'est pas connu de votre part. Dans le futur, pour l'ensemble des enfants aux prises avec un TCC-L, les retombées attendues incluent une meilleure connaissance de leurs difficultés. Les résultats pourraient éventuellement orienter le développement de moyens d'intervention efficaces pour ces enfants afin de réduire l'impact de leur difficultés auditives sur leurs activités au quotidien.

8) Inconvénients et risques

Aucun risque n'est associé aux tâches que devra accomplir votre enfant ni aux mesures que nous recueillerons. Cependant, la participation de votre enfant aux évaluations pourrait entraîner un certain état de stress ou de fatigue. Aussi, la pose du bonnet utilisé en électrophysiologie pourrait lui occasionner un certain inconfort (possibilité d'irritations lors de la préparation du cuir chevelu pour l'installation des électrodes). De courtes pauses sont prévues pour contrer la fatigue et la baisse de motivation. Des pauses supplémentaires peuvent être prises au besoin.

9) Confidentialité

Tous les renseignements obtenus sur votre enfant dans le cadre de cette recherche seront confidentiels, à moins d'une autorisation de votre part ou d'une exception de la loi tel qu'indiqué dans la *Loi sur la protection de la jeunesse* où des renseignements confidentiels peuvent être communiqués s'il existe un motif raisonnable de croire qu'un risque sérieux de mort ou de blessures graves menace une personne ou un groupe de personnes identifiable et que la nature de la menace inspire un sentiment d'urgence (article

72.8 - *Loi sur la protection de la jeunesse*). Nous allons remplacer son nom par un code. Les dossiers seront conservés sous clef dans une filière au laboratoire de recherche de Benoît Jutras et les documents contenant vos coordonnées ou celles de votre enfant seront détruits cinq ans suivant la fin de cette étude ousuivant la publication des données reliées à l'étude. Quant aux données, elles seront conservées jusqu'à dix ans après leur publication. Les données codées seront partagées avec les co-chercheurs du projet de recherche à des fins d'analyses. De plus, afin de vérifier la saine gestion de la recherche, il est possible qu'un délégué du comité d'éthique de la recherche consulte les données de la recherche. Par ailleurs, les résultats de cette étude pourront être publiés ou communiqués dans des congrès scientifiques mais aucune information permettant d'identifier votre enfant ne sera alors dévoilée. À des fins de protection,le Ministère de la santé et des services sociaux pourrait avoir accès à votre nom et prénom ainsi que ceux de votre enfant, ses coordonnées, la date de début et de fin de sa participation au projet jusqu'àun an après la fin de ce projet.

10) Indemnité compensatoire

Une somme forfaitaire de 15$ sera remise en compensation des frais de déplacement, pour chacune des rencontres prévues pour ce projet de recherche.

11) Liberté de participation

La participation de votre enfant à l'étude est entièrement libre et volontaire. Vous et votre enfant pouvez refuser de participer à l'étude et vous pouvez annuler votre consentement en tout temps sans préjudice. Vos données ne seront pas utilisées et seront détruites advenant que vous décidez de vous retirer de l'étude.

12) Clause de responsabilité

En signant ce formulaire de consentement, vous ne renoncez à aucun de vos droits prévus par la loi ni à ceux de votre enfant. De plus, vous ne libérez pas les investigateurs de leur responsabilité légale et professionnelle advenant une situation qui causerait préjudice à votre enfant.

13) En cas de questions ou de difficultés

Pour plus d'informations concernant cette recherche, contactez le chercheur responsable (codirecteur de l'étudiante au doctorat) de cette étude au CHU Sainte-Justine, Benoît Jutras, , l'étudiante au doctorat, Fauve Duquette- Laplante ou la directrice de thèse, Amineh Koravand. Pour l'Hôpital de Montréal pour enfants – CUSM veuillez contacter la chercheure responsable Isabelle Gagnon (Pour tout renseignement sur vos droits à titre de participant à ce projet de recherche, vous pouvezcontacter le commissaire local aux plaintes et à la qualité des services du CHU Sainte-Justine au (514) 345-4749, de l'Hôpital de Montréal pour enfants – CUSM : (514) 412-4400 poste 22223, ou le Bureau d'éthiqueet d'intégrité de la recherche de l'Université d'Ottawa (ethique@uottawa.ca) au (613) 562-5387.

14) Consentement et Assentiment

a. Consentement du parent relatif à la participation de son enfant à l'étude

On m'a expliqué la nature et le déroulement du projet de recherche. J'ai pris connaissance du formulaire de consentement et on m'en a remis un exemplaire. J'ai eu l'occasion de poser des questions auxquelles on a répondu. Après réflexion, j'accepte que mon enfant participe à ce projet de recherche.

_____
Nom de l'enfant

_____ _____ _____
Nom du parent/tuteur Signature du parent/tuteur Date

b. Consentement du parent à participer à la recherche

Le traitement de l'information auditive d'enfants d'âge scolaireayant subi un traumatisme crâniocérébral

On m'a expliqué la nature et le déroulement du projet de recherche. J'ai pris connaissance du formulaire de consentement et on m'en a remis un exemplaire. J'ai eu l'occasion de poser des questions auxquelles on a répondu. Après réflexion, j'accepte de compléter les questionnaires.

Nom du parent/tuteur	Signature du parent/tuteur	Date

c. Assentiment de l'enfant à participer à l'étude

On m'a expliqué le projet de recherche et j'accepte d'y participer.

(Signature de l'enfant)	Date

d. Consentement du parent relatif au contact de l'enseignant

On m'a expliqué la nature et le déroulement du projet de recherche. J'ai eu l'occasion de poser des questions auxquelles on a répondu. Après réflexion, j'accepte que l'équipe de recherche contacte l'enseignant de mon enfant afin qu'il donne des informations sur mon enfant à partir du questionnaire « *Échelle des comportements auditifs* ».

Nom de l'enseignant-e:_____ École : _____

Téléphone/courriel :_____

15) Formule d'engagement de la personne déléguée par le chercheur

J'ai expliqué au participant ou à son parent/tuteur ou aux deux à la fois tous les aspects pertinents de la recherche et j'ai répondu aux questions qu'ils m'ont posées. Je leur ai indiqué que la participation au projet de recherche est libre et volontaire et que la participation peut être cessée en tout temps.

Nom de la personne qui a obtenu le consentement (lettres moulées)	Signature	Date

16) Interprète

a. Interprète utilisé? Oui ☐ Non ☐ S.O. ☐

Si un interprète a été utilisé, langue d'interprétation : _____

Nom de l'interprète	Signature de l'interprète	Date

Appendix B

B.1. Article 5

The article, in the following form, was published in *Applied Neuropsychology: Child*.

Duquette-Laplante, F., Macaskill, M., Jutras, B., Jemel, B., & Koravand, A. (2023). Brain functional connectivity in children with a mild traumatic brain injury: A scoping review. *Applied Neuropsychology: Child*, 1–12. https://doi.org/10.1080/21622965.2023.2293248

Title

Brain functional connectivity in children with a mild traumatic brain injury: A scoping review

F. Duquette-Laplante [a,b,c]*, M. Macaskill[d] , B. Jutras[b,c], B. Jemel[b,e] and A. Koravand[a]

[a]*Audiology and Speech Pathology Program, School of Rehabilitation Sciences, University of Ottawa, Ottawa, Canada;* [b]*School of Speech-Language Pathology and Audiology, Université de Montréal, Montreal, Canada;* [c]*Research Center, CHU Sainte-Justine, Montreal, Canada;* [d]*Centre de Recherche en Audiologie pédiatrique, Hôpital Necker, Paris, France;* [e]*Research Laboratory in Neurosciences and Cognitive Electrophysiology, Research Center CIUSS-NIM, Hôpital Rivière des Prairies*

*Corresponding author: Fauve Duquette-Laplante, School of Speech-Language Pathology and Audiology, Université de Montréal, C.P. 6128, succursale Centre-ville, Montréal, Québec, Canada H3C 3J7,

Abstract

Introduction: The occurrence of mild traumatic brain injury(mTBI) is estimated at 0,2-0,3% cases annually. Following a mTBI, some children experience persistent symptoms, and functional connectivity (FC) changes may be implicated. However, characteristics of FC have not been widely described in this population. This scoping review aimed to identify and understand the impacts of mTBI on EEG-measured FC in children, provide an overview of the available literature, detail analysis techniques, and describe gaps in the research. **Methods:** PubMed, Web of Science, Medline, Embase, ProQuest and CINAHL were searched up to June 25, 2023, with the terms child, mTBI, EEG, FC, and their synonyms. Ten studies were identified. **Results:** Five studies reported significant differences between the mTBI group and controls. In addition to group differences, six studies reported significant variation over time. Brain Network Analysis (BNA), utilized in seven studies, was the primary FC analysis recorded. Two of the five studies that reported significant differences following mTBI utilized the BNA. The other three applied alternative analysis methods. **Discussion:** FC assessment based on EEG can identify some differences in children with mTBI. BNA was more useful in following changes over time. Further research is suggested, considering the limited age range and number of retrieved studies.

Keywords: functional connectivity; EEG; electroencephalography; mTBI; concussion

1. Introduction

It has been estimated that more than 3 million children worldwide suffer from a traumatic brain injury (TBI) each year (Dewan et al., 2016; Hawley et al., 2003). With a range of severity from mild to moderate to severe, TBIs can have devastating impacts, such as death or permanent disability (Thurman, 2016). However, between 70 and 90% of TBI cases are mild (Dewan et al., 2016; Thurman, 2016). Mild traumatic brain injury (mTBI) is defined as a traumatic physiological disruption of the brain (Mild Traumatic Brain Injury Committee, American Congress of Rehabilitation Medicine, 1993). This could occur in one of three situations: when the head is struck or hits an object or when the brain goes through an acceleration and deceleration motion – whiplash (Mild Traumatic Brain Injury Committee, American Congress of Rehabilitation Medicine, 1993). While most children with mTBI have a good prognosis and recover within a few weeks, some will experience persistent cognitive, physical, and emotional symptoms that can significantly impact their quality of life (Barlow et al., 2010; Zemek et al., 2016). Following a mTBI, 9% (Barlow et al., 2010) to 31% (Zemek et al., 2016) of children may suffer from persistent symptoms. Unfortunately, the initial symptom profile does not accurately predict whether symptoms will persist, leading to suffering even in children with good initial outcomes (Babcock et al., 2013). Additionally, mTBI is susceptible to misdiagnosis and is overlooked years later. The exact neural mechanisms underlying the persistence of symptoms are not yet fully understood, but studies have suggested that alterations in functional connectivity (FC) may play a role (Barr et al., 2012; Cao & Slobounov, 2009; Kumar et al., 2009; Liu et al., 2021; Mayer et al., 2011; Stevens et al., 2012; Thatcher et al., 1989; Vergara et al., 2018). Understanding the contributing neural mechanisms is critical for developing effective interventions to support these children and prevent long-term sequelae.

The FC refers to the temporal correlation between activity in different brain regions during rest or task performance (Friston et al., 1993). FC is different from structural connectivity, which refers to the physical connection between the different brain regions, and effective connectivity, which is the causal relationship between brain structures, regions and activity (Friston et al., 1993; Friston et al., 2011; Gerstein et al., 1989). FC is related to processes that generally implicate long-distance structures, such as memory (Babiloni et al., 2004; Hanouneh et al., 2018), emotions (Lee & Hseih, 2014), or inner thoughts (Berkovich-Ohana et al., 2014). FC can also be implicated in the relay of

information from and to adjacent structures and regions. In EEG, FC is represented by the signal coupling between the signal recorded from two distinct electrode sites. It is typically measured using functional magnetic resonance imaging (fMRI), which uses changes in blood oxygenation levels to measure and map activity in the brain, or electroencephalography (EEG), which uses electrical activity to achieve the same purpose (Friston et al., 1993). It reflects functional communication between different areas of the brain and can be altered in various neurological and psychiatric disorders, including mTBI (Cao & Slobounov, 2009). fMRI studies report altered FC following pediatric TBI but with significant variability in altered FC patterns (Dona et al., 2017; Borich et al., 2015; Newsome et al., 2015; Westfall et al., 2015).

Although EEG research on children with mTBI is limited, using such a technique to study FC provides multiple advantages over fMRI, PET or MEG. EEG is easily accessible, non-invasive, and has a high temporal resolution, allowing for the investigation of neural processes with high temporal precision. EEG is also more cost-effective than fMRI, which is advantageous in clinical settings. Furthermore, some recent EEG studies investigating FC in adults with mTBI have yielded promising results. For example, altered FC was identified in the frontal, parietal and occipital regions in acute and chronic phases of mTBI compared to healthy controls (Cao & Slobounov, 2009; Liu et al., 2021). Such results position recording changes in FC as a proper tool to monitor altered FC following the injury.

This scoping review aims to uncover and catalogue the current research on EEG-measured FC in children suffering from mTBI, the methods used to analyze EEG-measured FC, and the findings reported. The results of this scoping review will have important implications for identifying gaps in the literature and advancing the understanding of the neural mechanisms underlying persistent symptoms in children with mTBI and the methods suited to analyze these alterations in the EEG-measured FC. This information can help identify the need for future research directions and in developing interventions and rehabilitation protocols to support children with mTBI and prevent long-term consequences.

2. Methods

This scoping review complies with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis extension for Scoping Reviews (Tricco et al., 2018). The five stages of the Scoping

review framework developed by Arksey and O'Malley (2005) were followed: Stage 1: identifying the research question; Stage 2: identifying relevant studies; Stage 3: study selection; Stage 4: charting the data; Stage 5: collating, summarizing and reporting the results.

2.1. Eligibility Criteria

Studies published in peer-reviewed journals from their inception up to June 2023 in either English or French (articles originally published in languages other than English or French were not excluded, provided a full-text translation was available) evaluating functional connectivity in children with mTBI were eligible for inclusion. The search strategy focused on studies in the pediatric population (age 2-18 years – this age group was labeled under the generic term "children" in the article) that had experienced either concussion or mTBI. Studies targeting primarily moderate to severe or acquired brain injury were excluded. Studies using EEG methods to assess FC were included in the review. In terms of EEG analysis methods, there were no restrictions. Both qualitative and quantitative analysis methods were included.

2.2. Information Sources and Search Strategy

A comprehensive search was conducted, encompassing publications from the inception of the database up to August 15, 2022, with an update search on June 25, 2023. The search focused on articles containing the terms 'child' in conjunction with 'pediatric', 'concussion', 'mild traumatic brain injury', 'EEG', 'functional connectivity', and related synonyms. These terms were searched in the titles, abstracts, keywords, and full texts of the articles. All search strategies were established in consultation with a health sciences librarian at the University of Ottawa to identify studies across the following databases: PubMed, Web of Science, Medline, Embase, and ProQuest (see Supplementary Material for the full search strategies).

2.3. Study Selection

Studies were reviewed in two stages. The first stage consisted of screening titles and abstracts, while the second stage was to read the entire articles. In order to avoid bias or error, three reviewers were involved in both stages. Where any conflicts arose regarding the eligibility of studies, the three reviewers discussed the study together to reach a consensus. The exclusion criteria were revised partway through the selection process to reject studies that did not separately

analyze pediatric and adult patients or mild and moderate brain injury. Figure 1 shows the flow chart of the study selection process.

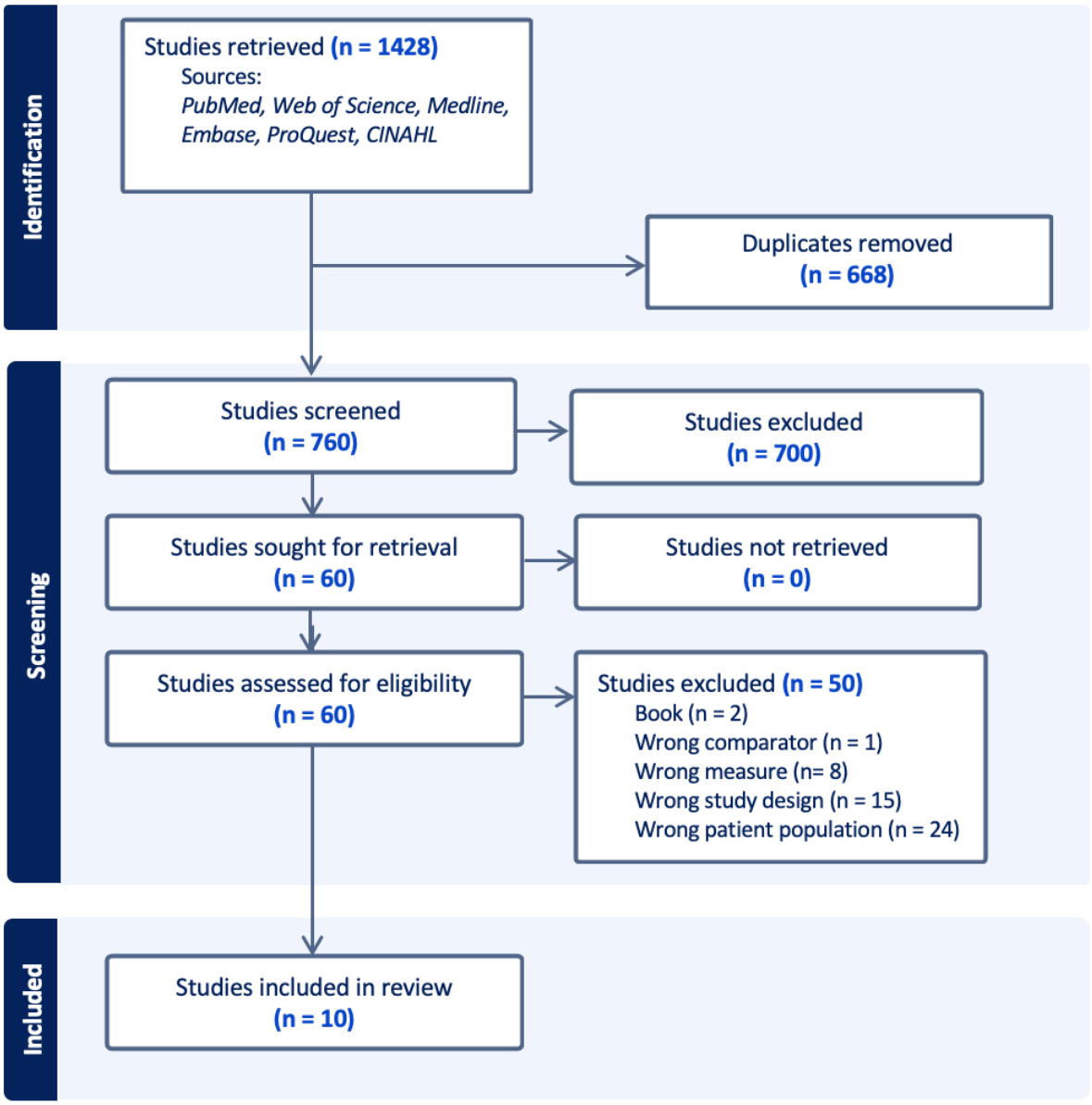

Figure 1. PRISMA diagram.

2.4. Data Charting Process and Data Items

A data-charting form was developed by all three reviewers in Microsoft Excel to determine the variables of interest. Data categories included publication characteristics (e.g., year and journal of

publication, country in which data was collected) and study characteristics (e.g., study design, number of participants, participant characteristics, etc.). The studies were divided between two reviewers, JT and JJ and were extracted independently. A third reviewer, FDL, reviewed the extraction for consistency and clarity.

3. Results

3.1. Selection of sources of evidence

A total of 1428 studies were imported to Covidence for initial review (Covidence systematic review software, n.d.). After duplicates were removed, 760 articles remained for the title and abstract screening. Following the title and abstract screening, 60 articles proceeded to full-text review. After a full-text review, ten articles were retained for extraction.

3.2. Characteristics of sources of evidence

The ten included articles were published between 2014 and 2021 and originated from either Canada (Boshra et al., 2020; Virji-Babul et al., 2014) or the United States (Broglio et al., 2016, 2018; Ferraracci et al., 2021; Howell et al., 2018, 2021; Kiefer et al., 2015; Kontos et al., 2016; Reches et al., 2017). Articles were published across nine journals with impact factors ranging from 1.31 to 4.67.

3.3. Outcomes

3.3.1. Studies characteristics

In terms of study design, all ten studies included had a prospective design. The majority of studies (Boshra et al., 2020; Broglio et al., 2016; Ferraracci et al., 2021; Howell et al., 2021; Reches et al., 2017; Virji-Babul et al., 2014) used a comparison cohort design, where the comparison group consisted of typically-developing children. Two studies (Broglio et al., 2018; Howell et al., 2018) use a prospective cohort design without a comparison group, although Howell et al. (2018) created a reference network for comparison of results. Two studies (Boshra et al., 2020; Kontos et al., 2016) compared two test groups to a control group. Kontos et al. (2016) compared a group of concussed patients with post-traumatic migraine (PTM) to a group of concussed patients without PTM in addition to the control group. Boshra et al. (2020) compared patients with acute concussion

to healthy controls as well as patients with chronic concussion, though patients with chronic concussion were older (mean age 57.3); therefore, this data was not considered in this review. One case study was also included (Kiefer et al., 2015). Further details of the study characteristics can be found in Table 1.

Table 1. Summary of Characteristics of the Included Studies (N=10).

Study	Design	Number of participants		Participant Age (in years)	Matching	Type of brain injury	First EEG Measure	Follow-up Schedule
		Test Group	Control Group					
Broglio et al., (2016)	Cohort - prospective (comparison)	24	21	Experimental mean = 16.3 ± 2.2 yrs Control mean = 17.1 ± 2.9 yrs	Athletes, matched for gender, sport, age, height, and weight	Sport-related concussion	Within 10 days post injury	**Visits at:** symptomatic (10 days post injury), self-report asymptomatic (4 days post symptom resolution), return to play (4 days post medical clearance to return to sport), post-asymptomatic (1 month post symptom resolution) time points
Broglio et al., (2018)	Cohort - prospective (comparison)	46	31	Participant mean = 15.9 + 0.9 yrs	Athletes, in non-contact sports e.g. track, basketball, etc.	Sport-related concussion (self-identified)	Pre-football season	**Visits at:** pre-season, midseason, and post-season time points
Boshra et al., (2020)	Cohort - prospective (comparison)	Acute = 26 Chronic = 19	Acute = 28 Chronic = 20	Experimental mean (acute) = 15.4 yrs Control mean (acute) = 19.2 yrs	Acute group: Healthy participants *Data from the chronic group comparisons was not analysed in this review*	Acute concussion	20.15 days post injury	None
Ferraracci et al., (2019)	Cohort - prospective (comparison)	21	15	Experimental mean = 14.97 ± 2.7 yrs Control mean = 13.8 ± 2.6 yrs	School-aged participants (8-18 years) whom have never experienced a TBI	mild brain injury (mTBI)	1-19 months post-injury	None
Kiefer et al., (2015)	Case report study - prospective (no comparison)	1		15 yrs	RBNM based on healthy subjects	Sport-related concussion	18h post injury	**Visits at**: 18h, 21, 50 and 116 days post injury
Howell et al., (2018)	Cohort - prospective (no comparison) /longitudinal study	20		8-18 yrs	RBNM based on 70 females and 50 males aged 25–50 (mean age = 38.4,SD = 7.2)	Sport-related concussion	Within 10 days post injury	None
Howell et al., (2021)	Cohort - prospective (comparison)	36	31	Experimental mean = 14 ± 2.3 yrs Control mean = 14.6 ± 2.2 yrs	Athletes, matched based on the age, sex, and body size	Sport-related concussion	Within 10 days post injury	**Visits at**: <10 days post injury, ~3 weeks post injury, after return-to-play clearance.
Kontos et al., (2016)	Cohort - prospective (comparison)	PTM = 15 No PTM = 22	Control = 20	Experimental mean PTM = 16.45 yrs Experimental mean No PTM = 16.50 yrs	Subjects matched based on age sex, and concussion history	Sport-related concussion	1 week post injury	**Visits at**: 1, 2, 3, and 4 weeks post-injury

				Control mean = 18.35 yrs				
Reches et al., (2017)	Cohort - prospective (comparison)	80	81	14-24 yrs old Experimental mean = 16.4 yrs Control mean = 17.4 yrs	Subjects matched for the time elapsed between visits	Sport-related concussion	2–10 days post injury	**UPMC** **Visits at**: 2-10 days post-injury; 3 follow-up visits at 7 (±2) days from previous visit **UMHS** **Visits at**: 2-10 days post-injury; asymptomic, return to play, one month after return to play time points
Virji-Babul et al., (2014)	Cohort - prospective (comparison)	9	33	Experimental mean = 16.5 yrs Control mean = 16 yrs	Soccer players	Sport-related concussion	26 days (± 35) post injury	None

3.3.2. Participants characteristics

Exclusion criteria. Half of the studies did not explicitly detail exclusion criteria (Boshra et al., 2020; Broglio et al., 2016, 2018; Kiefer et al., 2015; Virji-Babul et al., 2014). Exclusion criteria were explicitly mentioned in the remaining half of the studies (Ferraracci et al., 2021; Howell et al., 2018, 2021; Kontos et al., 2016; Reches et al., 2017). Patients with a previous history of head injury and illicit drugs or medication affecting the central nervous system (Ferraracci et al., 2021; Kontos et al., 2016; Reches et al., 2017), as well as patients with a history of psychiatric disorder (Howell et al., 2018, 2021; Kontos et al., 2016; Reches et al., 2017) were typically excluded. Two studies (Kontos et al., 2016; Reches et al., 2017) also mentioned that they excluded patients with severe TBI or brain surgery, a history of additional mild TBI in the six months prior to injury, any neurological or psychiatric disorder, substance abuse or current use of any medication affecting the central nervous system, as reported by the participants.

Sample group characteristics. In studies with one test group of individuals with mTBI, (Broglio et al., 2016, 2018; Ferraracci et al., 2021; Howell et al., 2018, 2021; Reches et al., 2017; Virji-Babul et al., 2014), sample size ranged from 9-80 with an average sample size of 28. Two studies included multiple test groups: Kontos et al. (2016) and Boshra et al. (2020). Kontos et al. (2016) divided the test group into patients with PTM (n=15) and without PTM (n=22), while Boshra et al. (2020) divided their test group into patients with acute and chronic concussions; the latter

comprised older patients (mean age = 57.3 years). Therefore, this data was not considered in this review.

Aside from Boshra et al. (2020), the mean age of participants in the sample group ranged from 14 to 16.5 years of age. As suggested by the mean age of participants, most studies focused on teenage participants. Studies were also aimed primarily at athletes (Broglio et al., 2016, 2018; Howell et al., 2018, 2021; Kiefer et al., 2015; Kontos et al., 2016). The sex of the test group was mixed in all studies, with the exception of Virji-Babul et al. (2014).

Most studies focused on sports-related concussions, except for Boshra et al. (2020) and Ferraracci et al. (2021), where the mechanism of injury was unspecified. All studies either had mTBI confirmed or diagnosed by a medical professional (Boshra et al., 2020; Broglio et al., 2016; Ferraracci et al., 2021; Kiefer et al., 2015; Kontos et al., 2016; Reches et al., 2017) or reported them as clinically diagnosed (Boshra et al., 2020; Broglio et al., 2018; Howell et al., 2018, 2021; Virji-Babul et al., 2014). Two studies (Howell et al., 2018, 2021) referenced the Berlin Consensus statement for concussion, which is defined as a traumatic brain injury caused either by a direct blow to the head, face, neck or elsewhere in the body with an impulsive force, transmitted to the head resulting in the rapid onset of impairment of neurological function (McCrory et al., 2017) as their diagnostic criteria for their studies. The other studies did not specify their definition of mTBI or concussion for the diagnosis of their participants (Broglio et al., 2016, 2018; Virji-Babul et al., 2014). All studies specified that a medical professional, such as a physician or psychologist, confirmed concussions.

The first EEG measures were recorded between 1 week and less than three months following injury in the acute or subacute phase. Details regarding the type, number, and diagnostic criteria for brain injuries, as well as the delay between brain injury and recording of EEG and follow-up time, can be found in Table 1.

In all studies, the control group consisted of participants with no concussion history. Three of ten studies specified that participants were matched in terms of age and sex, among other criteria (Broglio et al., 2016; Howell et al., 2021; Kontos et al., 2016). The remaining studies did not indicate any matching procedures. Further details can be found in Table 1.

3.3.3. Patient state

EEG recordings can be measured in either an active or passive state, i.e., during a task or at rest. Of the ten studies, the majority (8) performed measures during a task (Boshra et al., 2020; Broglio et al., 2016, 2018; Howell et al., 2018, 2021; Kiefer et al., 2015; Kontos et al., 2016; Reches et al., 2017). Ferraracci et al. (2021) and Virji-Babul et al. (2014) performed measures at rest, and Boshra et al. (2020) included measures at rest and during a task, although only results recorded in the active condition were analyzed. Further details can be found in Table 2.

Only two of the ten selected studies (Ferraracci et al., 2021; Virji-Babul et al., 2014) reported resting-state analysis findings. Such measurements are generally performed in two ways: eyes closed, and eyes opened. Ferraracci et al. (2021) included measures in both conditions, while Virji-Babul et al. (2014) only recorded in an eye-closed condition. In the other eight studies, patients were asked to perform a task during the EEG recording (Boshra et al., 2020; Broglio et al., 2016, 2018; Howell et al., 2018, 2021; Kiefer et al., 2015; Kontos et al., 2016; Reches et al., 2017). In some studies, recordings were performed during two separate tasks (Broglio et al., 2016; Kiefer et al., 2015). An oddball task was utilized in six of the eight selected studies (Boshra et al., 2020; Broglio et al., 2016, 2018; Howell et al., 2021; Kiefer et al., 2015; Reches et al., 2017) while a Go/No-go task type was used in four studies (Broglio et al., 2016; Howell et al., 2018; Kiefer et al., 2015; Kontos et al., 2016).

The oddball task consisted of asking participants to attend to a series of stimuli and respond to a randomly occurring target stimulus while ignoring other stimuli. Typically, one or more types of target stimuli are presented infrequently, known as the deviant/s (10-20% of presentations), and a frequently occurring stimulus, known as the standard stimulus (80-90% of presentations), which is to be ignored. Over several repeated trials, participants respond to the deviant stimuli, typically by counting the number of presentations or pressing a button for each presentation. The most commonly used oddball paradigm (Broglio et al., 2016, 2018; Howell et al., 2021; Kiefer et al., 2015; Reches et al., 2017) included a 2 kHz tone as the standard stimulus (80% of presentations), a 1 kHz tone as the deviant target (10% of presentations), and additionally included a novel stimulus (10% of presentations). The novel stimulus was a variety of environmental sounds or noises that patients were instructed to ignore (Broglio et al., 2016, 2018; Howell et al., 2021; Kiefer

et al., 2015; Reches et al., 2017). This allowed for analyzing network associations with the standard, deviant, and novel presentations. Boshra et al. (2020) also used an oddball task. However, they did not include a novel stimulus and instead used a multi-deviant paradigm. In this paradigm, the standard stimulus was a – 50 ms 1 kHz 80 dB SPL – tone. Each of the three deviants differed from the standard stimulus in one of three domains: (1) duration – 100 ms instead of 50 ms; (2) intensity – 90 dB SPL instead of 80 dB SPL and frequency – 1.2 kHz instead of 1 kHz. Each deviant represented 6% of presentations for a total of 18%, while the standard stimulus represented 82%. All paradigms required the participants to press a button to indicate a response.

The second type of task used in four of the eight selected studies was a Go/No-go task (Broglio et al., 2016; Howell et al., 2018; Kiefer et al., 2015; Kontos et al., 2016). A Go/No-go task is similar to an oddball task in which participants respond to a target stimulus while ignoring other stimuli. However, in a Go/No-go task, the target stimuli are presented frequently, and the non-target stimuli are presented infrequently. As such, the go/no go task is designed to measure the participant's ability to ignore or withhold a response to stimuli rather than their ability to attend to or respond to the target stimuli. This task involves cognitive functions such as response inhibition, executive function, and sustained attention. Broglio et al. (2016), Kontos et al. (2016), and Kiefer et al. (2015) used an auditory Go/No-go task, and Howell et al. (2018) used a visual task. However, Kiefer et al. (2015) did not describe or analyze the task results. Broglio et al. (2016) utilized a paradigm where the target and non-target stimuli differed based on pitch. A 2 kHz tone was the target stimulus, which represented 80% of trials, and a 1 kHz tone was the non-target stimulus, which represented the remaining 20% of trials. Kontos et al. (2016) described the target as a "high beep" and the non-target as a "low beep" with target and non-target stimuli representing 80% and 20% of trials, respectively. Howell et al. (2018) used a visual Go/No-go paradigm, which used letters as stimuli. Target stimuli were random letters, making up 80% of trials, whereas the non-target stimulus was the letter X, making up the other 20% of trials. All paradigms used a button press to indicate a response.

Table 2. Summary of Recording Parameters of the Included Studies (N=10).

Reference	Number of Electrodes	Online Filter	Sampling rate	Equipment	Movement and blink removal	Number of Recordings	Time post injury (first measure)	Paradigm	Analysis performed
Broglio et al., (2016)	256 Ag/AgCl electrodes	Bandpass filter : 0.1-100Hz	256 Hz	Electrical Geodesics, Inc.	Not mentioned	4	6,2 ± 2.4 days	Auditory oddball task; Auditory Go/No-go task	BNA analysis
Broglio et al., (2018)	256 Ag/AgCl electrodes	Reference to 2016 study : Bandpass filter: 0.1-100Hz	reference to 2016 study : 256 Hz	reference to 2016 study : Electrical Geodesics	Not mentioned	3	Pre-season (Jun to mid-Aug); Mid-season (Sep to early-Nov); Post season (Nov- Dec).	Auditory oddball task	BNA analysis
Boshra et al., (2020)	64 Ag/AgCl electrodes	Bandpass filter: 0.01-100Hz	512 Hz	Biosemi ActiveTwo system	Non-ocular artefacts removed using visual inspection. Eye-movement and blink related artifacts removed using independent component analysis.	1	AC: M = 20,15 days	Auditory oddball task (measures recorded at rest were not analyzed in the article)	Magnitude-squared coherence; Power spectrum; Weighted Phase Lag Index
Ferraracci et al., (2019)	19 tin electrodes	High pass filter: 1.5 Hz; Low pass filter: 60 Hz	256 Hz	BrainMaster Technologies Inc. Discovery 24E	Automated drowsiness and eye movement rejection options in the Neuroguide software.	1	1-19 months (M = 8,4; SD = 5,4)	Measures at rest (eyes open and closed)	Principal component analysis
Kiefer et al., (2015)	128-electrode wet EEG cap	Bandpass filter: delta (0.5-4 Hz), theta (3-8 Hz), alpha (7-13 Hz) and beta (12-30 Hz)	250 Hz	Not mentioned	Not mentioned	5	18h	Auditory oddball task; (Go/No-go task performed but data not analyzed)	BNA-based ERP analysis
Howell et al., (2018)	64-channel electrical Food and Drug Administration (FDA) - cleared net	Not mentioned	Not mentioned	Electrical Geodesics, Inc.	Not mentioned	1	7 ± 2.5 days	Visual Go/No-go task	BNA analysis
Howell et al., (2021)	64-channel electrical Food and Drug Administration (FDA) - cleared net	Not mentioned	Not mentioned	Electrical Geodesics, Inc.	Not mentioned	3	Median 7, IQR 4-9 days	Auditory oddball task	BNA analysis
Kontos et al., (2016)	128 Ag/AgCl electrode cap	Not mentioned	256 Hz	Electrical Geodesics, Inc. and Biosemi ActiveTwo system	Exclusion of epochs not corresponding to correct motor responses and with excessive electrical activity (>100µV).	4	1 week	Auditory Go/No-go task	BNA Analysis

Reches et al., (2017)	128 (UPMC) or 256 (UMHS)	Not mentioned	250 Hz	Electrical Geodesics, Inc.	Eye-movement and blink related artifacts removed using independent component analysis	4	2-10 days	Auditory oddball task	BNA analysis
Virji-Babul et al., (2014)	64-channel Hydrogel Geodesic SensorNets	Not mentioned	250 Hz	Net Amps 300 Electrical Geodesics, Inc.	Not mentioned	1	≤3 months	Measures at rest	Graph theory analysis and application of a network learning model

3.4. Method of Analysis

FC analysis can be done in different ways. Of the ten studies collected, seven analyzed their data according to the Brain Network Activation method (Broglio et al., 2016, 2018; Howell et al., 2018, 2021; Kiefer et al., 2015; Kontos et al., 2016; Reches et al., 2017). Boshra et al. (2020) and Ferraricci et al. (2021a) used coherence measures. Boshra et al. (2020) included weighted phase-lock index (WPLI) coherence measures, and Ferraricci et al. (2021) conducted a Principal Component Analysis (PCA) before analyzing coherence. Virji-Babul et al. (2014) used a graph theory analysis.

Brain Network Analysis. The Brain Network Analysis (BNA) was the primary functional connectivity analysis recorded in this review as it was used in seven studies (Broglio et al., 2016, 2018; Howell et al., 2018, 2021; Kontos et al., 2016; Kiefer et al., 2015; Reches et al., 2017). As described in detail by Shahaf and collaborators (2012), the BNA algorithm can be summarized as a measure that compares two things: 1) groups' brain activity patterns and 2) individual brain activity patterns to the brain activity pattern of a group of individuals. It aimed to provide a score of similarity between the individual's and a group's brain activity pattern in order to classify the individual in one group or the other (Shahaf et al., 2012). Via electrical brain potentials evoked with a task such as the Go/no-go paradigm, the BNA algorithm was described to utilize stimuli onset to identify and extract temporally related sequential events (“peak-pairs”) at specific locations and frequency bands. Significant “peak-pairs” were identified when a predetermined number of participants (cluster) would present with the same “peak-pairs” (Shahaf et al., 2012). Patterns of these events were calculated, and those with too few participants were discarded. To

develop comparison groups, patterns were compared between groups in order to determine the most discriminating patterns in each group (Shahaf et al., 2012). Such patterns were identified as a characterization of this specific group's brain network activity (Reches et al., 2013; Shahaf et al., 2012). In the context of mTBI, children's brain activity following an mTBI was recorded and compared to a control group reference network or to the brain activity recorded from a control group.

Magnitude Square Coherence (MSC). Measures of coherence provide a measure of phase angle consistency between two or more electrodes. In other words, coherence can describe the degree of linear similarity between two signals, e.g. two channels, in terms of their power spectrum, i.e. the brain regions they represent. This method was used by Ferraricci et al. (2021) and Boshra et al. (2020). As noted above, Ferraricci et al. (2021) performed a PCA prior to calculating coherence values, as described by Bastos & Schoffelen (2016) and Friston et al. (2012).

Weighted Phase-Lag Index (WPLI). Boshra et al. (2020) also used the Weighted Phase-Lag index (WPLI). Unlike MSC, which focuses on the magnitude or power of signals from different regions, WPLI focuses on phase differences, comparing two different areas in the brain (Bastos & Schoffelen, 2016; Vinck et al., 2011).

Graph Theory Analysis. Virji-Babul et al. (2014) used a Graph theory, which characterizes the brain as a network and then describes the network in terms of density, global efficiency, clustering coefficient, and modularity (Bastos & Schoffelen, 2016; Sporns, 2010; van Wijk, Stam, & Daffertshofer, 2010).

Some types of connectivity analysis are based on activity comparisons in different regions and, therefore, require identifying specific areas of interest. Boshra et al. (2020) used MSC and WPLI to measure amplitude-related and phase-related synchronization. They identified six regions of interest (ROIs) and separated the ROIs according to both hemispheres of the brain: the Left (L) with odd-numbered electrodes and the Right (R) with even-numbered electrodes. The areas were then separated into three regions of interest related to the cortex's lobes: Frontal (F), Temporal (T) and Parietal (P). Each region was represented by a cluster of 2-3 electrodes: L-F (F3, F5 and F1); R-F (F4, F2 and F6); L-T (T7 and CP5); R-T (T8 and CP6); L-P (P3 and P1); and R-P (P4 and P2). Measures of coherence and WPLI between the three different regions allowed the authors to

make inferences about different connectivity types, reporting on four categories of connectivity: Interhemispheric, Intrahemispheric long-range, Intrahemispheric mid-range and Intrahemispheric within-region. Ferraracci et al. (2021) also used a coherence analysis, focusing on the coherence between the frontal region, represented by two (of 19 total) electrodes, FP1 and FP2, individually, and the rest of the cortex, represented by various other individual electrodes. Principal component analysis was conducted on the remaining 17 electrodes to uncover regions coherent with the frontal electrodes and select those regions for statistical analysis. Virji-Babul et al. (2014) interpolated their 64 electrodes into 27 ROIs computed with the BESA Virtual Standard 10-10 Average montage. All 27 nodes were included in the analysis, where both brain connectivity modelling and graph theoretical analysis were conducted.

3.5. Findings

Findings regarding the analysis method were reported differently. Four out of ten included studies found significant differences between the mTBI group and control groups (Boshra et al., 2020; Ferraracci et al., 2021; Reches et al., 2017; Virji-Babul et al., 2014). Utilizing the BNA score, Kontos et al. (2016) indicated that mTBI participants presented with lower BNA scores when compared to the controls. With a magnitude square coherence analysis, Boshra et al. (2020) found significant group differences in all frequency bands. Boshra et al. (2020) detailed results revealing interhemispheric, intrahemispheric, and within-range differences between mTBI and control participants, and WPLI analysis indicated group differences within all frequency bands. They reported altered functional connectivity as hyperconnectivity immediately after the injury, leading to decreased functional connectivity over time compared to age-matched controls (Boshra et al., 2020). Results from Ferraracci et al. (2019) were similar, as their principal component analysis revealed reduced coherence and functional connectivity in their mTBI participants, especially in the beta frequency band. Virji-Babul et al. (2014) found partially significant results, indicating that the overall functional connectivity was not significantly different between groups. However, they found increased connectivity in specific local networks in the prefrontal cortex and occipital gyrus (Virji-Babul et al., 2014).

Second to group differences, specific articles also reported significant variation over time (Broglio et al., 2016, 2018; Howell et al., 2021; Kiefer et al., 2015; Kontos et al., 2016; Reches et al., 2017).

Broglio et al. (2018) recruited football and non-contact sport athletes for their study and found a group increase in both groups in BNA scores from their first test pre-season to post-season, two to three months later. Kiefer et al. (2015) measured the BNA score at five intervals and found a decrease immediately following the injury, with a steady increase in score over the subsequent visits, with their score returning to preinjury level at 116 days postconcussion. Howell et al. (2021) reported that BNA scores decreased over the testing timeline (approximately three weeks) in their concussion group but increased over time for their control group. Furthermore, Kontos et al. (2016) found that participants with mTBI had significantly lower BNA scores than controls at the initial measurement and one-week post-injury. That difference remained significant at three weeks post-injury. Reches et al. (2017) reported changes over time in the BNA score following the mTBI, where overall scores increased between the first visit and the second visit, approximately seven days later, for all mTBI patients. They indicated that there were significant BNA differences between the control group and the mTBI group at the first visit but not the second, indicating recuperation for the mTBI patients.

However, half of the studies (Broglio et al., 2016, 2018; Howell et al., 2018, 2021; Kiefer et al., 2015) selected for this review did not find significant differences between the control and experimental groups. One was a case study (Kiefer et al., 2015). Therefore, there was no group comparison. The other four studies (Broglio et al., 2016, 2018; Howell et al., 2018, 2021) used the BNA score, and none found significant differences between their mTBI participants and healthy controls.

4. Discussion

4.1. Summary of Results

The main goal of this scoping review was to identify the available literature and understand the impacts of mTBI on FC in children. Only ten articles could be identified, all published within the last ten years, with the oldest article being published in 2014. Indeed, this suggests that functional connectivity measured with EEG is a relatively new concept, especially in the target population. In terms of outcome measures, results were heterogenous, with approximately half the articles (Boshra et al., 2020; Ferraracci et al., 2021; Reches et al., 2017; Virji-Babul et al., 2014) reporting significant group differences. There was significant variability in terms of methods and participant

characteristics that might account for these mixed results. The analysis method seemed to play a significant role in the variability of results recorded in the reported studies. The BNA method was reported in seven studies, and only one study of these noted significant group differences. The three other studies employed an analysis method other than the BNA method, and all reported significant differences. These results suggest that the heterogeneity of significant findings does not support the use of only one connectivity analysis method. As the BNA provides a more standardized method, methodological heterogeneity does not explain the discrepancy in results; however, BNA does not offer data for region-specific analyses. In the included studies, the BNA resulted in a score out of 100, which gave minimal information regarding the specific distinctions between groups in different brain areas' FC modulations. Such limited information can be useful in return-to-play programs and clinical settings, but it does not appear to be suited for pinpointing the underlying neurophysiological mechanisms of mTBI.

In contrast, the significant group differences reported by the three remaining studies, which did not employ the BNA analysis, provided more specific information in this regard (Boshra et al., 2020; Ferraracci et al., 2021; Virji-Babul et al., 2014). These studies' methods allowed researchers to focus on specific regions of interest and may also explain why they are more sensitive to changes in FC. For example, significant changes in connectivity (increased and decreased) have been recorded specifically in the frontal regions of mTBI patients in adults (Cao & Slobounov, 2010; Thatcher et al., 1989) and in children (Ferraracci et al., 2021; Virji-Babul et al. 2014). Frontal regions are generally related to attention-driven mechanisms, processing speed and executive functions (Chan, 2005; Levin et al., 2008). These capacities have been shown to be altered following an mTBI (Chan, 2005; Levin et al., 2008). The diversity of analytic approaches employed with adults and adolescents, if repeated with children of all ages, could lead to a better understanding of the specific attributes relating to children's mTBIs (Cao & Slobounov, 2009; Chan, 2005; Levin et al., 2008; Liu et al., 2021).

No study analyzed a comparison between resting-state and task-based connectivity. Both articles that examined FC at a resting state found significant differences between the control and experimental groups (Ferraracci et al., 2021; Virji-Babul et al., 2014). In fact, in both studies, a reduction in connectivity at a baseline level was related to higher mTBI symptoms (Virji-Babul et al., 2014) or reduced processing speed (Ferraracci et al., 2021). In addition, Virji-Babul et al.

(2014) investigated the global network in children with mTBI, and no FC alteration could be found. This aligns with what is known about this population, which has heterogeneous clinical manifestations of minimal symptoms. A paradigm with both resting-state and tasked-based FC recordings could facilitate the understanding of how baseline differences tie into group differences and if resting-state recordings are more sensitive to mTBI than tasked-based recordings.

Participants' profiles could also contribute to the heterogeneity in the results between studies. Contrary to the homogeneity in age, other participant characteristics, such as the injury criteria and the control group inclusion criteria, varied greatly across studies. Most studies did not report the exact diagnosis process or injury mechanism for the participants involved in their research. Inclusion and exclusion criteria for control groups were also disparate between the different studies. Certain studies conducted a comprehensive mTBI history and excluded participants with any history of mTBI (Ferraracci et al., 2021; Kontos et al., 2016; Reches et al., 2017), whereas others reviewed mTBI history up to only six months prior (Kontos et al., 2016; Reches et al., 2017). Many studies also had athletes in the control group (Broglio et al., 2016, 2018; Howell et al., 2021; Virji-Babul et al., 2014). Hessen et al. (2006) and Klonoff et al. (1993) have shown that it is possible for symptoms from previous mTBI to persist in time (many years) and indicated that changes in the brain could be measured years after the concussion. In general, it has been shown that athletes (contact sport or not) are more at risk of suffering from a mTBI than non-athletes (Veliz et al., 2017). The history of mTBI, the persistence of symptoms, and the fact that mTBI can often go unreported (Cassidy et al., 2004; Thurman, 2016) are potential biases that could reduce group differences, especially in the studies that did not account for those factors (Broglio et al., 2016, 2018; Howell et al., 2021; Kontos et al., 2016; Reches et al., 2017; Virji-Babul et al., 2014). Missing previous mTBI history information underlines the necessity for stricter exclusion criteria when selecting the participants.

The model of connectivity following mTBI proposed by Boshra et al. (2020) postulated that FC is increased in the acute stage and diminished in the chronic stage. Findings in connectivity patterns, similarly to adult studies, vary and can partly be explained by the focus of each study and the time following the injury. This is supported by Boshra et al.'s (2020) model, as they also found overall hyperconnectivity in their acute cohort but reduced connectivity in their chronic cohort. These

results, taken together, imply that the impact of the mTBI on FC is not linear, and further research is needed in order to better understand how it is affected following an mTBI.

4.2. Generalizability of the results

The results of the current study cannot be generalized to the breadth of the pediatric population because the average age of the participants in the ten reported studies was 14 to 16 years old (Boshra et al., 2020; Broglio et al., 2016, 2018; Ferraracci et al., 2021; Howell et al., 2018, 2021; Kiefer et al., 2015; Kontos et al., 2016; Reches et al., 2017; Virji-Babul et al., 2014). The inclusion criteria for multiple studies included in this review were set as low as eight years of age, but most studies included very few, if any, 8-year-olds in their sample. Even if the search strategies for the current review included children between the ages of 2 and 18 years old, there were no articles on children younger than eight years old or specific studies excluding teenagers. Children's developing brain tends to demonstrate more plasticity than adults (Huttenlocher & Dabholkar, 1997), and recovery outcomes for children differ from those of adults (Yeates et al., 2009; Hessen et al., 2007). Therefore, young children's FC may be modulated differently than adults. Such a concept is supported by Reches et al. (2017) results. In their study, they reported that a significant difference between BNA scores could only be recorded when including 16 years old and older participants in their experimental and control groups. They reported that when including the fourteen and fifteen year olds, there were no significant differences between groups. This supported the need for research in children, as there are potentially significant differences in FC modulations between different age groups. The lack of available studies for those age groups prohibits a global understanding of mTBI's impact on children's FC.

4.3. Literature Gaps and Future Research Directions

This review aimed to compile data regarding EEG-measured FC in children with mTBI. The current scoping review has uncovered certain gaps in the current literature, and recommendations for future studies can be expressed. A more stringent control selection should be performed to reduce potential comparison bias. Indeed, studies made comparisons with older male adults (Boshra et al., 2020) or with control groups with whom concussion was only excluded if it happened less than six months prior (Reches et al., 2017; Virji-Babul et al., 2014), the differences or lack thereof between groups was hard to interpret. Controls should, therefore, be with no

previous history of head injury. Moreover, as the term concussion is large, a more detailed description of the diagnosis criteria employed to diagnose mTBI participants in the study could be warranted. Research has shown that distinct children age groups are at risk of different mTBI injury mechanisms, as those younger than 4 years are most at risk of falling, school-aged children of motor vehicle accidents, and teenagers of sports-related injuries (Trefan et al., 2016). Such contrasting injury mechanisms warrant more exploratory studies with younger children. As children's brains develop through childhood into adolescence, multiple processes, such as synaptic pruning and myelination, occur (Paus et al., 1999; Whitford et al., 2007). Having more age group representation could help gain insight into the impacts of mTBI on such crucial moments of change in the brain. Longitudinal studies measuring the impact of mTBI on FC over time in children are warranted as changes in FC are dynamic and vary over time. This type of study will confirm or infirm Boshra et al.'s (2020) postulated adult model, indicating hyperconnectivity measures after the injury subsides into reduced connectivity. Analysis methods such as magnitude coherence, the PCA, the WPLI or the graph theory are needed to explore specific FC modulations in children. All these methods found, to some extent, significant differences between children groups. Studies comparing resting-state and paradigm-based FC measures should be conducted. Resting-state-related results reported in this study were promising, as reduced FC was related to higher deficits related to mTBI (Ferraracci et al., 2021; Virji-Babul et al., 2014). As EEG is generally available in all hospitals and resting state is easy and fast to record, such a method could easily be included in the evaluation following an mTBI when visiting the emergency room. The analysis of resting state FC in other pediatric populations could offer further insight into the developing brain. No study undertook such a comparison, and it could help understand the subtle changes in FC following the mTBI. A better understanding of these subtle changes could offer better insight into dysfunctions and the persistence of symptoms following mTBI. These changes could also provide information to clinicians, children's caregivers and school personnel regarding the remediation and recuperation potential of different symptoms following mTBI. However, much research is still needed to give a sufficient overview of how FC is affected by mTBI in children. With the development of portable EEG technology, the increase in wearability outside a lab environment could help in furthering such research as such assessments could also be conducted outside of the hospitals and in the community.

5. Scoping review limitations

A potential bias for this review was its focus on only mTBI. Studies with participants with mild to severe TBI without grouping per severity were excluded and missed. The reported severity of symptoms and impacts on the brain following a moderate to severe TBI are well documented, and including this population could have influenced the results because this study was centred around mTBI. The report and mTBI diagnostic criteria for multiple studies were vague and not detailed, which could introduce bias from the selection of the study participants reported in this review. There is no global consensus on which term to use when diagnosing concussion or mTBI. The term concussion is generally more utilized in sports and mTBI in the general population. As they do not have the same diagnosis criteria and definition, it could introduce bias in participants and severity of symptoms. This review focused on children aged between 2 and 18 years. However, no study could be found on children younger than eight years old, and the average age of all studies was between 14-16 years old, leaving a gap in the understanding of the impact of mTBI on functional connectivity in younger children.

6. Acknowledgments

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7. Declaration of Interest statement

The authors have declared that no conflict of interest existed at the time of publication.

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Supplementary Material

Search strategies per database

Key terms

The following key terms and their synonyms were targeted:

1. Child
2. Concussion, mild traumatic brain injury
3. Electroencephalography (EEG)
4. Functional connectivity

PubMed ***n=155, August 15th 2022; n=199, June 25th 2023***

(((pediatric* or paediatric* or child* or preschool* or pre-school* or kindergarten* or kindergarden* or elementary school* or nursery school* or schoolchild* or toddler* or boy or boys or girl* or middle school* or pubescen* or juvenile* or teen* or youth* or high school* or adolesc* or pre-pubesc* or prepubesc*) AND (Concussion* or sub-concussive brain injury* or concussed* or mild traumatic brain injury* or brain damage* or mild acquired brain injury* or cranio-cerebral trauma* or head injury*)) AND (EEG* or fcEEG* or electroencephalography* or electroencephalogram* or electrophysiology* or neurophysiology*)) AND (Functional connectivity* or cortical connectivity* or temporal coincidence* or functional interaction* or functional network)

PsycINFO ProQuest ***n=396, August 15th 2022; n=483, June 25th 2023***

(pediatric* OR paediatric* OR child* OR preschool* OR pre-school* OR kindergarten* OR kindergarden* OR elementary school* OR nursery school* OR schoolchild* OR toddler* OR boy OR boys OR girl* OR middle school* OR pubescen* OR juvenile* OR teen* OR youth* OR high school* OR adolesc* OR pre-pubesc* OR prepubesc*)
AND
(Concussion* OR sub-concussive brain injury* OR concussed* OR mild traumatic brain injury* OR brain damage* OR mild acquired brain injury* OR crania-cerebral trauma* OR head injury*)
AND
(EEG* OR fcEEG* OR electroencephalography OR electroencephalogram* OR electrophysiology* OR neurophysiology*)
AND
(Functional connectivity* OR cortical connectivity* OR temporal coincidence* OR functional interaction* OR functional network)

Web of Science ***n=50, August 15th 2022; n=55, June 25th 2023***

Advanced search

1. (pediatric or paediatric" or child" or preschool" or pre-school" or kindergarten* or kindergarden" or elementary school" or nursery school" or schoolchild" or toddler* or boy or boys or girl" or middle school" or pubescen" or juvenile' or teen" or youth or high school or adolesc* or pre-pubesc" or prepubesc").mp. [mp=title, abstract, heading word, table of contents, key concepts, original title, tests & measures, mesh word]

2. (Concussion or sub-concussive brain injury or concussed" or mild traumatic brain injury or brain damage" or mild acquired brain injury or crania-cerebral trauma" or head injury").mp. [mp=title, abstract, heading word, table of contents, key concepts, original title, tests & measures, mesh word]

3. (EEG or fcEEG or electroencephalography" or electroencephalogram* or electrophysiology" or neurophysiology").mp. [mp=title, abstract, heading word, table of contents, key concepts, original title, tests & measures, mesh word]

4. 4 (Functional connectivity or cortical connectivity or temporal coincidence" or functional interaction" or functional network).mp. [mp=title, abstract, heading word, table of contents, key concepts, original title, tests & measures, mesh word]

5. 1 and 2 and 3 and 4

Ovid EMBASE ***n=23, August 15th 2022; n=27, June 25th 2023***

Advanced search

1. (pediatric* or paediatric* or child* or preschool* or pre-school* or kindergarten* or kindergarden* or elementary school* or nursery school* or schoolchild* or toddler* or boy or boys or girl* or middle school* or pubescen* or juvenile* or teen* or youth* or high school* or adolesc" or pre-pubesc* or prepubesc").mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]
   (outcome* or predic* or progn* or factor* or indicat*).mp.
2. (Concussion* or sub-concussive brain injury* or concussed* or mild traumatic brain injury or brain damage* or mild acquired brain injury* or cranio-cerebral trauma* or head injury").mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]
3. (EEG* or fcEEG* or electroencephalography* or electroencephalogram* or electrophysiology* or neurophysiology").mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]

4. (Functional connectivity* or cortical connectivity* or temporal coincidence* or functional interaction* or functional network).mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub- heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]

5. 1 and 2 and 3 and 4

CINHAL ***n=6, August 15th 2022; n=9, June 25th 2023***

(ALL ((pediatric OR paediatric OR child* OR preschool* OR pre-school* OR kindergarten* OR kindergarden* OR elementary AND school* OR nursery AND school* OR schoolchild OR toddler* OR boy OR boys OR girl* OR middle AND school* OR pubescen* OR juvenile* OR teen* OR youth* OR high AND school* OR adolesc* OR pre-pubesc* OR prepubesc*)) AND ALL ((concussion* OR sub-concussive AND brain AND injury* OR concussed* OR mild AND traumatic AND brain AND injury* OR brain AND damage* OR mild AND acquired AND brain AND injury OR crania-cerebral AND trauma* OR head AND injury*)) AND ALL ((eeg* OR fceeg* OR electroencephalography* OR electroencephalogram* OR electrophysiology* OR neurophysiology*)) AND ALL ((functional AND connectivity* OR cortical AND connectivity* OR temporal AND coincidence* OR functional AND interaction* OR functional AND network))

Ovid MEDLINE ***n=10, August 15th 2022; n=15, June 25th 2023***

Advanced search

1. (pediatric* or paediatric* or child* or preschool* or pre-school* or kindergarten* or kindergarden* or elementary school* or nursery school* or schoolchild* or toddler* or boy or boys or girl* or middle school* or pubescen* or juvenile* or teen* or youth* or high school* or adolesc" or pre-pubesc* or prepubesc").[mp=title, abstract, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword heading word, floating subheading word, candidate term word]

2. (Concussion* or sub-concussive brain injury or concussed or mild traumatic brain injury* or brain damage* or mild acquired brain injury* or cranio-cerebral trauma or head injury").mp. [mp=title, abstract, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword heading word, floating subheading word, candidate term word]

3. (EEG* or fcEEG* or electroencephalography or electroencephalogram* or electrophysiology* or neurophysiology").mp. [mp=title, abstract, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword heading word, floating subheading word, candidate term word]

4. (Functional connectivity* or cortical connectivity* or temporal coincidence* or functional interaction* or functional network).mp. [mp=title, abstract, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword heading word, floating subheading word, candidate term word]

5. 1 and 2 and 3 and 4