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Article

Exploring the relationship between resting-state intra-network connectivity and accelerometer-measured physical activity in pediatric concussion: a cohort study

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Abstract

Our objective was to explore the association between resting-state functional connectivity and accelerometer-measured physical activity in pediatric concussion. Fourteen children with concussion (aged 14.54 ± 2.39 years, 8 female) were included in this secondary data analysis of a larger study. Participants had neuroimaging at 15.3 ± 6.7 days postinjury and subsequently a mean of 11.1 ± 5.0 days of accelerometer data. Intra-network connectivity of the default mode network (DMN), sensorimotor network (SMN), salience network (SN), and frontoparietal network (FPN) was computed using resting-state MRI. We found that, per general linear models (GLMs), only intra-network connectivity of the DMN was associated with physical activity levels. More specifically, increased intra-network connectivity of the DMN was significantly associated with higher levels of subsequent accelerometer-measured light physical activity (LPA; $F_{(2,11)} = 7.053$, $p = 0.011$, $R_a^2 = 0.562$; $\beta = 0.469$), moderate physical activity (MPA; $F_{(2,11)} = 6.159$, p = 0.016, Ra2 = 0.528; $\beta = 0.725$), and vigorous physical activity (VPA; $F_{(2,11)} = 10.855$, $p = 0.002$, $R_a^2 = 0.664$; $\beta = 0.792$). Intra-network connectivity of the DMN did not significantly predict sedentary time. Therefore, these preliminary findings suggest that there is a positive association between the intra-network connectivity of the DMN and device-measured physical activity in children with concussion.

Key words: concussion, brain injury, exercise, physical activity, pediatric

Résumé

Notre objectif était d'explorer l'association entre la connectivité fonctionnelle à l'état de repos et l'activité physique mesurée par accéléromètre dans les commotions cérébrales pédiatriques. Quatorze enfants ayant subi une commotion cérébrale (âgés de 14,54 ± 2,39 ans, huit de sexe féminin) ont été inclus dans cette analyse des données secondaires d'une étude plus vaste. Les participants ont eu une neuro-imagerie 15,3 ± 6,7 jours après la blessure et par la suite une moyenne de 11,1 ± 5,0 jours de données d'accéléromètre. La connectivité intraréseau du réseau en mode par défaut (« DMN »), du réseau sensorimoteur (« SMN »), du réseau de saillance (« SN ») et du réseau fronto-pariétal (« FPN ») a été calculée à l'aide d'IRM fonctionnelle à l'état de repos. Nous avons constaté que, selon les modèles linéaires généraux, seule la connectivité intraréseaudu DMN était associée aux niveaux d'activité physique. Plus précisément, la connectivité intraréseau accrue du DMN était significativement associée à des niveaux plus élevés d'activité physique légère ($F_{(2,11)} = 7{,}053$, $p = 0{,}011$, $Ra^2 = 0{,}562$; $\beta = 0{,}469$), modérée ($F_{(2,11)} = 6{,}159$, $p = 0{,}016$, $Ra^2 = 0{,}528$; $\beta = 0{,}725$) et vigoureuse mesurée par accélérométrie ($F_{(2,11)} = 10{,}855$, $p = 0{,}002$, $Ra^2 = 0{,}664$; $\beta = 0{,}792$). La connectivité intraréseaudu DMN n'a pas prédit de manière significative le temps de sédentarité. Par conséquent, ces résultats préliminaires suggèrent qu'il existe une association positive entre la connectivité intraréseau du DMN et l'activité physique mesurée par un appareil chez les enfants ayant subi une commotion cérébrale. [Traduit par la Rédaction]

Mots-clés : commotion cérébrale, lésion cérébrale, exercice, activité physique, pédiatrie

Introduction

Concussions are mild traumatic brain injuries that result in functional neurological disturbance in the absence of gross structural damage (McCrory et al. 2017). While on the mild end of the brain injury spectrum, concussions can nonetheless result in enduring symptoms that negatively impact multiple aspects of daily living (Voormolen et al. 2019). In children, a population in which rates of concussion are increasing (Meehan III and Mannix 2010; Fridman et al. 2018; Veliz et al. 2021), nearly 30% experience symptoms that persist beyond the expected recovery window of 4 weeks (Barlow et al. 2010; Barlow 2016; McCrory et al. 2017). These symptoms can lead to quality-of-life deficits that can last for months (Fineblit et al. 2016; Novak et al. 2016; Plourde et al. 2018).

Increasingly, resting-state functional magnetic resonance imaging (rs-fMRI) has been used to study brain changes in pediatric concussion. rs-fMRI can be used to provide insight into areas of the brain that are synchronously active at rest (in the absence of any particular cognitive stimuli) to explore the functional neuropathology of concussion. Studying these networks provides insight into brain function in the healthy, injured, or diseased state, and whether there are spatial or temporal pathological features in the acquired functional brain signal, which may be indicative of clinical complications (O'Connor and Zeffiro 2019). While the brain regions and/or networks studied, time of imaging, and rs-fMRI analysis methods themselves have varied across studies, they consistently show that there are rs-fMRI disturbances in children with concussion in comparison to their healthy peers (Abbas et al. 2015; Borich et al. 2015; Newsome et al. 2016; Dona et al. 2017; Manning et al. 2017; Murdaugh et al. 2018; Iyer et al. 2019*a*, 2019*b*; Kaushal et al. 2019; Meier et al. 2020; Plourde et al. 2020; Stephenson et al. 2020). Collectively, these studies have shown patterns of both hyper- and hypo-connectivity within the initial weeks of injury (Rausa et al. 2020), abnormal rs-fMRI activity in children with protracted symptoms (Iyer et al. 2019*a*, 2019*b*), and a persistence of functional impairment in asymptomatic children who have been medically cleared to return-to-sport (Newsome et al. 2016).

With rs-fMRI disturbances in pediatric concussion now better characterized, studies have aimed at understanding the relationship between functional connectivity and other relevant and widely studied clinical outcomes including symptoms, sleep, cognition, and mood (Iyer et al. 2019*a*, 2019*b*; Kaushal et al. 2019; Gornall et al. 2021). However, the associations between resting-state brain activity and other salient features of pediatric concussion are still understudied. In particular, the impact of rs-fMRI activity on physical activity in pediatric concussion remains unexplored. Within the current landscape of concussion research and clinical management, wherein the importance of exercise has been increasingly recognized and established in recent years (Langevin et al. 2020; Carter et al. 2021), this represents a considerable knowledge gap. There is now a shift away from prolonged rest (Thomas et al. 2015; Grool et al. 2016), which was the former *status quo* in concussion management (Leddy et al. 2018). Submaximal aerobic exercise studies in concussion—and meta-analyses of them—suggest that engaging in physical activity within 2 weeks of injury improves symptoms (Lal et al. 2017; Langevin et al. 2020; Carter et al. 2021). Therefore, there is now considerable evidence that exercise, and conversely prolonged rest, have an impact on concussion recovery. What is not known is how the widely established rs-fMRI disturbances observed in pediatric concussion relate to sedentary time or physical activity levels postinjury.

With the recent wave of research on exercise in pediatric concussion, understanding the relationship between functional brain impairment and physical activity has become as germane as understanding the relationship between rs-fMRI and symptomatology or other clinical features. Therefore, in this exploratory study, we examined the relationship between intra-network rs-fMRI activity (within 4 widely researched and validated resting-state networks) and accelerometer-measured physical activity and sedentary time up to 1-month postinjury in children with concussion. It was hypothesized that reduced intra-network rs-fMRI activity (a measure of functional neuropathology) is associated with increased sedentary time and reduced physical activity levels.

Methods

The Hamilton Integrated Research Ethics Board approved this study. All participants provided informed consent, or assent in addition to parental consent, as appropriate.

Design

The data reported here were initially collected as part of the Back to Play study (DeMatteo et al. 2019), a larger cohort study (led by the senior authors) with the goal of informing return-to-activity guidelines for children with concussion. This report is a secondary data analysis of accelerometer and rs-fMRI data collected as part of the larger cohort. The present sample comprised only participants from the parent study with both neuroimaging data and subsequently collected accelerometer data (up to 1-month postinjury). Both males and females were included in the parent study with nearly equal representation (56% female, overall), with the current sample drawn from said cohort.

Participants

Participants in the parent study were recruited at McMaster Children's Hospital and/or its affiliated rehabilitation and sports medicine clinics. Patients who were diagnosed with concussion by a member of our clinical team were informed about the Back to Play study. Those interested in participating were referred to our research team for more information about study objectives, risks, and potential benefits. After this initial discussion, those intent on participating were consented (or assented, along with parental consent, if aged under 16 years) and recruited. An intake assessment was then scheduled by the research team as soon after the initial clinical consultation as possible. Exclusion criteria for the larger study included more severe injuries or those requiring more complex care. For the present study, patients were required to have neuroimaging and then subsequently at least 5 days of valid accelerometer wear.

Data collection procedures

Neuroimaging

All neuroimaging data were collected using a 3-Tesla GE Discovery 750 MRI scanner (with a 32-channel phased array receive coil) at the Imaging Research Centre (IRC) at St. Joseph's Healthcare, Hamilton. A screening questionnaire was performed by the IRC imaging technologist to ensure that the scan could be performed safely, and to inform patients and their families about the MRI procedure. The technologist then positioned the patient in the MRI, immobilizing their head with foam pads to minimize motion and to improve patient comfort.

The neuroimaging battery began with a 3-plane localizer with calibration sequences. Anatomical images were then collected, per a 3D inversion recovery (IR) prepped fast spoiled gradient recalled echo (SPGR) T1-weighted sequence (time to repetition/time to echo [TR/TE] = 11.36/4.25 ms, flip angle = 12°, interpolated 512 × 512 matrix, 22-cm field of view [FOV]). Immediately prior to the resting-state scan, a fieldmap was acquired (to correct for magnetic field inhomogeneities) using the same geometry as the functional scan (as follows). Resting-state functional data were collected using axial 2D acquisition, gradient echo echo planar imaging, TR/TE = 2000/35 ms, flip angle = 90°, 64 × 64 matrix, 300 time points (10 min), 22-cm FOV). During the resting-state scan, patients were asked to remain awake with their eyes open, and not think of "anything in particular".

Accelerometry

Patients were given a compact and light-weight waist-worn tri-axial accelerometer at their intake assessment (which occurred, on average, 4.71 ± 4.33 days before neuroimaging) to wear until self-reported symptom resolution, at which point the accelerometer was mailed back to the study team and acceleration data were downloaded. The accelerometer used in the Back to Play study was the ActiGraph GT3x (Pensacola, FL), which has demonstrated high reproducibility in measuring physical activity in acquired brain injury (Baque et al. 2016). Per the parent study, movement was recorded continuously at 30-Hz and downloaded into 3-s epochs. Patients were also given a logbook, in which they noted when the device was put on and off in the morning and evening, respectively, as well as any other times the device was removed (when participating in water-based activities, for example). Patients were instructed by the research team at the intake assessment to wear the accelerometer on the right hip during all waking hours, except for water activities, and how to use the logbook.

Data processing and analyses

Neuroimaging

All MRI preprocessing and analyses were performed in CONN 19c (Whitfield-Gabrieli and Nieto-Castanon 2012), which was run using SPM12 and MATLAB 2020a (Mathworks, Natick, MA). The only exception in the preprocessing pipeline was that functional data were unwarped using the B_0 maps acquired immediately prior to the rs-fMRI scan outside of CONN 19c using *epiunwarp* (Davis and Noseworthy 2016), which draws on functionality in FMRIB Software Library (FSL) (Smith et al. 2004; Jenkinson et al. 2012). The B_0-corrected maps were then uploaded into CONN 19c along with respective anatomical data for preprocessing.

The following steps were involved with preprocessing, and were guided by recommendations within CONN 19c and associated publications (Andersson et al. 2001; Henson and Friston 2007). First, functional data were realigned and coregistered to a reference image (and adjusted to the movement-defined deformation field associated with the reference image). Second, slice-timing correction was performed to time-shift and resample the rs-fMRI data to coincide with the midpoint of each TR. Third, using Statistical Parametric Mapping (SPM)'s Artifact Detection Tool (ART) (Ashburner et al. 2014), outlier scans in the functional data were flagged based on subject-motion exceeding a 0.9-mm framewise displacement or BOLD signal fluctuations >5 standard deviations (SD) from the mean signal. Fourth, functional data are normalized/registered to Montreal Neurological Institute (MNI) space, based on posterior tissue probability maps. Fifth, spatial smoothing was performed, with a Gaussian kernel of full-width at half-maximum of 6 mm. Subsequently, denoising was performed in CONN 19c, which involved 2 steps: (1) an anatomical component-based noise correction procedure (aCompCorr) to "regress out" noise components associated with cerebral white matter/cerebrospinal regions, outlier scans, subject motion (based on a 12-parameter affine transformation of the anatomical to functional data) (Friston et al. 1995; Behzadi et al. 2007; Power 2020), and (2) temporal filtering, using a filter ranging from 0.008 Hz and above 0.01 Hz. After both preprocessing and de-noising, data were inspected visually and per the quality assurance metrics in CONN 19c.

Once data were ready for analysis, intra-network connectivity of 4 widely studied and validated brain networks was computed (Fornito et al. 2016;), namely the default mode network (DMN), sensorimotor network (SMN), salience network (SN), and frontoparietal network (FPN) and physical activity in children with concussion. Intra-network connectivity was selected as the measure of choice for this preliminary investigation as it is representative of a resting-state network holistically, as has been shown in publications related to other neurological populations (Zhu et al. 2016; Houck et al. 2017; Ke et al. 2018; Lang et al. 2020).

Average within-network connectivity values were computed using the Matlab command line script conn_withinbetweenROItest, which extracted and exported single-subject intra-network correlation values, which were Fisher Z-transformed to improve normality. Seed regions are listed in Table 1.

Accelerometry

Data were downloaded from the ActiGraph GT3x devices using the accompanying software package, ActiLife Version 6 (Pensicola, FL). Triaxial accelerations collected at 30 Hz were downloaded into 3-s sampling intervals or epochs, which

Table 1. Seed regions used to calculate the intra-network connectivity of the 4 resting-state networks of interest.

Network	Seeds MNI coordinates (x, y, z)
DMN	Medial prefrontal cortex (1, 55, –3)
	Lateral parietal, left (–39, –77, 33)
	Lateral parietal, right (47, –67, 29)
	Posterior cingulate cortex (1, –61, 38)
SMN	Lateral seed, left (–55, –12, 29)
	Lateral seed, right (56, –10, 29)
	Superior seed (0, –31, 67)
SN	Anterior cingulate cortex (0, 22, 35)
	Anterior insula, left (–44, 13, 1)
	Anterior insula, right (47, 14, 0)
	Rostral prefrontal cortex, left (–32, 45, 27)
	Rostral prefrontal cortex, right (32, 46, 27)
	Supramarginal gyrus, left (–60, –39, 31)
	Supramarginal gyrus, right (62, –35, 32)
FPN	Lateral prefrontal cortex, left (–43, 33, 28)
	Lateral prefrontal cortex, right (41, 38, 30)
	Posterior cingulate cortex, left (–46, –58, 49)
	Posterior cingulate cortex, right (52, –52, 45)

Table 2. Average daily (in min/day) monitoring time and activity by intensity in our cohort.

	Mean	SD	Range
Monitoring time	798.3	68.0	686.8–914.5
Sedentary	631.0	75.9	504.2–733.2
LPA	116.1	33.9	68.9–172.2
MPA	28.6	11.3	13.4–48.6
VPA	22.7	16.9	3.3–57.8

Note: LPA = light physical activity, MPA = moderate physical activity, VPA = vigorous physical activity.

Table 3. Average intra-network connectivity across the 4 networks of study (as Fisher Z-transformed correlation coefficients).

	Mean	SD	Range
DMN	0.50	0.15	0.21–0.89
SMN	0.60	0.21	0.18–1.06
SA	0.48	0.11	0.23–0.70
FPC	0.58	0.16	0.34–0.81

Note: DMN = default mode network, FPN = frontoparietal network, SMN = sensorimotor network, SN = salience network.

were selected to reflect the median bout duration for high-intensity activities in children (Baquet et al. 2007). Once downloaded and converted into a 3-s epoch, wear-time validation was performed in ActiLife. First, a semiautomated procedure was performed to define a nonwear period of minimum length of 5-min. These periods were then inspected against the on- and off-times recorded in the patient logbooks, with nonwear periods excluded if they matched records from the patient log books. Days of accelerometer data without an associated log book entry were excluded. Data were then scored to determine activity intensity according to widely used Evenson cut-points (Evenson et al. 2012), which have the following activity count ranges: sedentary time (0–25 counts/15 s), light physical activity (LPA; 26–573 counts/15 s), moderate physical activity (MPA; 574–1002 counts/15 s), and vigorous physical activity (VPA; 1003 + counts/15 s).

Of note, participants in this study were in the early stages of concussion where guidelines recommended reduced levels of activity/more rest. While we considered applying the standard wear time validation algorithms developed by Choi et al. (2011) or Troiano/NHANES 2003–04, time spent resting (but awake) was often misclassified as nonwear resulting in a high number of nonvalid wear days. Therefore, we applied a semi-automated procedure that used a modified version of the Troiano algorithm to flag potential nonwear periods, and then confirmed nonwear using the log books completed by participants. Data were only excluded anytime the participant indicated they were not wearing the device, as well as any time they did not complete the log book to indicate the device was worn. It is also important to note that log book completion rates were relatively high for this study; out of a possible 167 days, only 12 days were excluded due to an incomplete log book.

Cleaned and scored data were then exported to SPSS Version 27 (IBM Corp. Released 2020. IBM SPSS Statistics for Windows, Version 27.0. Armonk, NY). Only children with more than 4-wear days of data, with each day comprised of more than 600 min of wear time, were included in the analysis (Rich et al. 2013). Any accelerometer data beyond 30 days postinjury were excluded from the current analysis, given that the scope of the study.

Statistical analyses

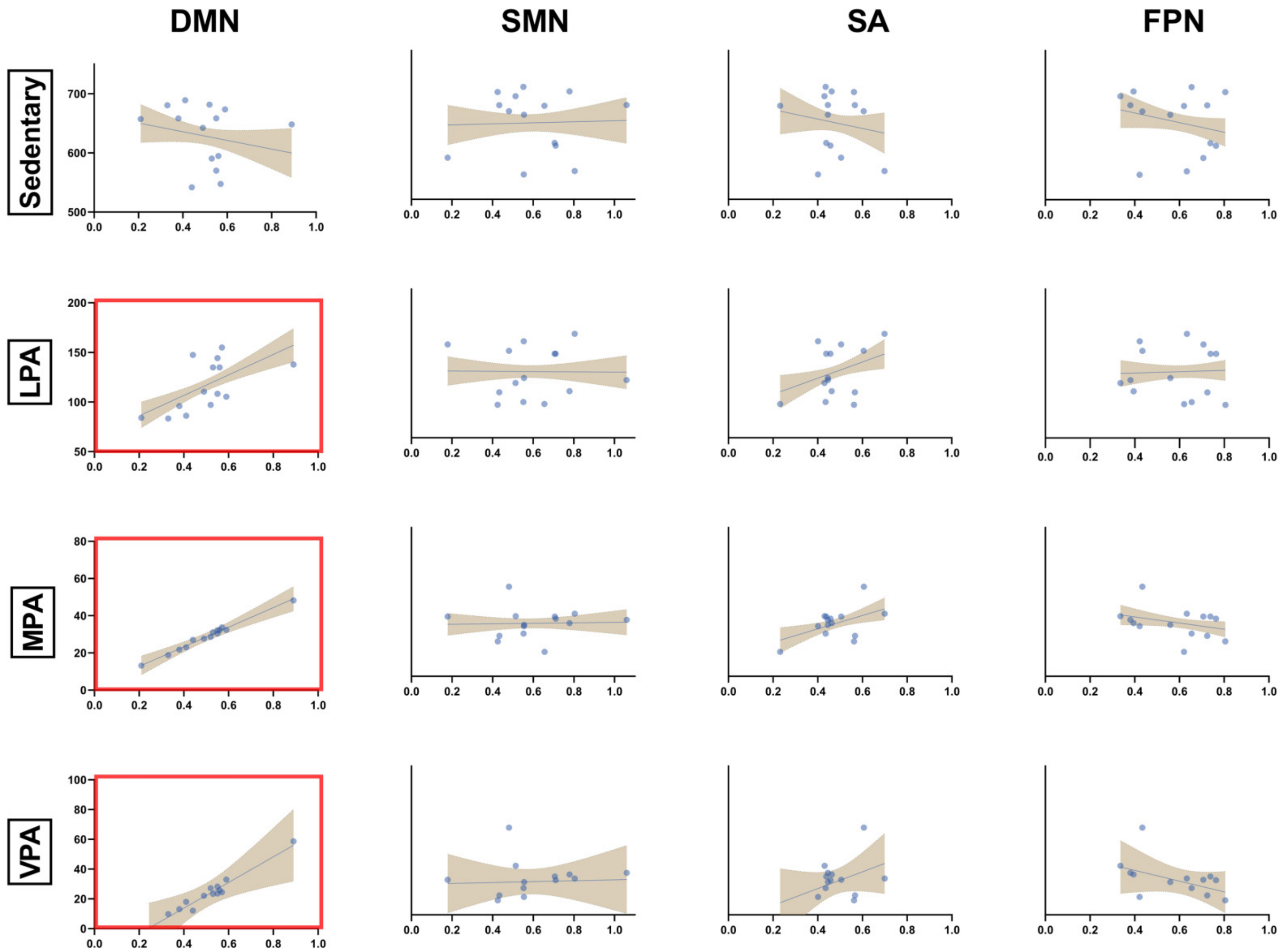
Across all valid wear days, average daily sedentary time, as well as average daily LPA, MPA, and VPA (in min/day) were calculated for cleaned and validated accelerometer cases in SPSS. These summary data (i.e., average sedentary time, LPA, MPA, and VPA, in units of min/day) were then imported into CONN 19c, wherein the *Calculator* tool was used to build a single-level general linear model (GLM) with intra-network connectivity and age as predictors of average daily activity (of the various intensities) or sedentary time across all days of accelerometer wear. Therefore, for each network of interest, 4 models were built to examine the association between intra-network rs-fMRI connectivity and average time per day in: LPA, MPA, VPA, and sedentary. Given the sample size of our study, additional variables were not included in the model; age was selectively chosen given that connectivity of resting-state networks has been shown to vary with age (Mak et al. 2017).

Results

Overview

Fourteen children with concussion (aged 14.54 ± 2.39 years, 8 female) were imaged at 15.3 ± 6.7 days postinjury and had an average of 11.1 ± 5.0 days of accelerometer data (with ≥ 600 min of wear-time per day) thereafter. Average daily monitoring time, sedentary time, and time spent in activity is summarized in Table 2.

Fig. 1. Model-predicted activity levels (in min/day) plotted against intra-network connectivity (Fisher Z-transformed correlation coefficients) and a linear fitted line. Only the models highlighted with a red box were significant. (LPA = light physical activity, MPA = moderate physical activity, VPA = vigorous physical activity). [Colour online.]



The groupwise average intra-network connectivity values for each of the networks studied are presented in Table 3 with associated standard deviations and ranges.

Relating brain activity and physical activity

From the series of GLMs, the only significant models (and the only network-related beta-coefficients that were significant) pertained to models including the DMN. The intra-network connectivity of the SMN, SA, and FPN did not predict accelerometer-measured sedentary time, LPA, MPA, or VPA. Fig. 1 shows the model-predicted activity levels (along with 95% confidence intervals) by activity type against intra-network connectivity. The figures show that with respect to the DMN, increased intra-network connectivity is closely associated with increased levels of activity, in particular MPA and VPA. Intra-network connectivity of the DMN was not; however, associated with average daily sedentary time.

The DMN-specific models and their relevant parameters for all intensities of activity are summarized in Table 4. Both unstandardized beta coefficients (B) and standardized beta coefficients (β) are provided for interpretation. Overall, there was a trend for decreased DMN intra-network connectivity predicting more sedentary time, and conversely, increased intra-network connectivity of the DMN was significantly associated with increased LPA, MPA, and VPA. For significant models, the residuals were normally distributed.

Discussion

This is the first study to examine the relationship between rs-fMRI impairment and subsequent activity levels in pediatric—or adult—concussion. While our findings are preliminary and exploratory, we demonstrate that intra-network connectivity within the DMN—but not the SMN, SA, or FPN—is associated with accelerometer-measured LPA, MPA, and VPA within the first month of injury in pediatric concussion. Adding to the literature demonstrating associations between DMN impairment and concussion symptoms, depression, anxiety, and sleep-impairment (Iyer et al. 2019*a*, 2019*b*), we show that intra-network connectivity within DMN may be implicated with physical activity within the first month of injury in children.

Table 4. General linear model parameters for DMN-specific analyses.

	B	95% CI for B	β	t	p
Sedentary time					
Predictor					
DMN	−71.633	−311.907, 168.640	−0.146	−0.656	0.525
Age	20.998	5.601, 36.395	0.667	3.002	0.012
Model	$F_{(2,\,11)} = 3.653$, $p = 0.061$, $R_a^2 = 0.458$				
LPA					
Predictor					
DMN	102.900	86.319, 289.261	0.469	2.346	0.039
Age	−8.486	−14.671, −2.301	−0.603	−3.020	0.012
Model	$F_{(2,\,11)} = 7.053$, $p = 0.011$, $R_a^2 = 0.562$				
MPA					
Predictor					
DMN	52.908	19.627, 86.189	0.725	3.499	0.005
Age	−0.394	−2.527, 1.739	−0.084	−0.407	0.692
Model	$F_{(2,\,11)} = 6.159$, $p = 0.016$, $R_a^2 = 0.528$				
VPA					
Predictor					
DMN	88.755	44.565, 128.945	0.792	4.526	0.001
Age	1.148	−1.555, 3.852	0.164	0.935	0.370
Model	$F_{(2,\,11)} = 10.855$, $p = 0.002$, $R_a^2 = 0.664$				

Note: β = standardized beta coefficient, B = unstandardized beta coefficient, LPA = light physical activity, MPA = moderate physical activity, VPA = vigorous physical activity.

The DMN and physical activity

Originally, the DMN was considered to be a "day dreaming network", active in the absence of external stimuli as a type of neural baseline (Buckner et al. 2008). However, more recent research on the DMN has shown that it is also associated with higher-order cognitive processes and can be active during goal-oriented thoughts and tasks. More specifically, studies now show that the DMN can be engaged when individuals imagine or plan for the future (Konishi and Bohbot 2013). Other studies suggest that the DMN is important in cognitive processes that result in immediate action or interfere with present behavioural goals (Smallwood et al. 2013). In adults, the DMN has also been linked to "internal mentation", or introspective thoughts about constructs such as the future or personal intentions (Andrews-Hanna 2012; Stawarczyk and D'Argembeau 2019). Together, these findings would suggest that DMN impairments may have the capacity to influence planned behaviours, such as participation in physical activity, and that DMN impairments can alter how information about physical activity behaviours are perceived, processed, and planned. This would help explain our findings, wherein only the DMN was found to be associated with subsequent levels of physical activity. Further research is needed to build on this possibility.

Prior research shows that in young adults with concussion, compared with healthy controls, a submaximal aerobic fitness test resulted in functional disturbance of the DMN (Slobounov et al. 2011; Zhang et al. 2012). More specifically, said test reduced internetwork connectivity between seed regions of the DMN, namely the PCC and the lateral parietal ROI, PCC, and the right lateral parietal ROI, and the PCC and MPFC (Zhang et al. 2012). Adding to this, our study suggests that intra-network impairment of the DMN may have an impact subsequent physical activity in children with concussion. Given that many studies have demonstrated DMN impairment in pediatric concussion (Newsome et al. 2016; Dona et al. 2017; Manning et al. 2017; Iyer et al. 2019*a*, 2019*b*; Kaushal et al. 2019; Meier et al. 2020; Plourde et al. 2020), and that our recent work demonstrates that children with concussion are less active than their healthy peers, the current findings suggest that widespread DMN impairment is associated with reduced levels of activity in children with concussion. Larger pediatric concussion cohorts are required to more definitively characterize the relationship between resting-state brain activity and physical activity.

Exercise and concussion management

The status quo in concussion management is changing. The traditional "rest-is-best" approach is being supplanted by an "exercise-is-medicine" mindset (Leddy et al. 2018). However, the present study suggests that in pediatric concussion, DMN impairment (which is a common in concussion) has a moderate association with physical activity. This underscores the need for physicians to actively advise pediatric concussion patients to engage in safe, submaximal aerobic exercise after a short (24–48 h) period of rest, as suggested by current guidelines (McCrory et al. 2017). Otherwise, if DMN impairment interferes with the ability to plan, engage with, or initiate physical activity, patients with DMN impairment may not be physically active, and this precludes them from experiencing the benefits of LPA on concussion symptoms. Furthermore, in the ultimate interest of promoting physical activity, interventions such as mindfulness (which is a meditative practice designed to help individuals become more aware and present of their current situation) can be prescribed acutely given their positive impact on the functional connectivity of the DMN (Bauer et al. 2020; Brewer et al. 2011; Berkovich-Ohana et al. 2012; Wang et al. 2014; Doll et al. 2015; Phillips et al. 2020). Mindfulness is not a contraindication to any other medications that may be prescribed after concussion, and it has other established benefits in brain injury, including improved self-efficacy (Azulay et al. 2013; Paniccia et al. 2019). Future research is needed in this area.

Generalizability

Our findings need to be studied in adults to understand if they generalize outside of a pediatric context, as several factors may make our findings pediatric-specific. For example, DMN functional connectivity is age-dependent, peaking in adulthood while being less coherent during childhood and senescence (Mak et al. 2017); physical activity also decreases with age (Guthold et al. 2018). This would suggest that the association between intra-network functional connectivity of the DMN and physical activity may be variable in children when compared with adults. Furthermore, cardiorespiratory fitness is related to the functional integrity of multiple brain networks, including the DMN (Voss et al. 2016). While the present study did not control for cardiorespiratory fitness (though all participants had sport-related injuries and were physically active prior to injury), similar studies in adults should control for this metric given that it declines nonlinearly and in an age-dependent rate in adults (Jackson et al. 2009), which may be confounding in adult samples with large age variance.

Limitations

This secondary data analysis is limited by the sample size. Larger studies examining the relationship between the DMN and postconcussion physical activity are warranted. We also cannot rule out the possibility that greater DMN impairment is associated with more severe symptoms that may, in turn, reduce participation in physical activity. Furthermore, this study did not exhaustively study all resting-state networks and/or anatomical regions; future research should expand on the regions of interest. There are also other rs-fMRI and accelerometer analysis methods that can be used to characterize the relationship between brain activity and physical activity. The impact of physical activity on resting-state networks in pediatric concussion also warrants study.

Conclusions

This exploratory study is the first to examine the association between intra-network connectivity and accelerometer-measured physical activity in pediatric concussion. We found that intra-network connectivity of the DMN—but not the SMN, SA, or FPN—was significantly associated with levels of LPA, MPA, and VPA performed within the first month after pediatric concussion. Given the increasing role of aerobic exercise in concussion management, and that the DMN is commonly perturbed following injury, children with concussion may be less likely to be physically active. Clinical management should continue to encourage participation in submaximal aerobic activity in the acute stages of injury.

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BS and BWT conceptualized and designed the study. CD maintained oversight over the parent study, and MDN maintained oversight over imaging analyses. BS and MDN performed imaging analyses. BS and JO performed accelerometry analyses. BS wrote the first draft of the manuscript. All the authors revised and approved the final version of the manuscript.

Competing interests

The authors declare there are no competing interests.

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