RESTING-STATE FUNCTIONAL CONNECTIVITY IN COLLISION AND CONTACT FEMALE ATHLETES OVER THE COURSE OF A SEASON

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A THESIS SUBMITTED TO
THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF ARTS

GRADUATE PROGRAM IN PSYCHOLOGY
YORK UNIVERSITY
TORONTO, ONTARIO

April 2021

ABSTRACT

Objective: University contact and collision sport athletes are exposed to numerous impacts to the body and head, however, the short-term effects of such cumulative hits on neurological functioning remain elusive. This study examined resting-state functional connectivity (rsFC) of brain networks in a sample of female varsity athletes over the course of a season.

Design: 19 female university athletes involved in contact (N = 7) and collision (N = 12) sports underwent functional MRI scans at both pre- and post-season. A group-level independent component analysis (ICA) was used to investigate differences in rsFC over the course of a season and differences between contact and collision sport athletes. Follow-up analyses examined the main effects of contact group and time.

Results: Decreased rsFC was observed over the course of the season between the default mode network (DMN) and regions in the frontal, parietal, and occipital lobe (pFDR < 0.05). Follow-up analyses indicated that these differences were driven by pre-season vs. post-season differences in the contact group. There was also a main effect of group, showing increased rsFC between the dorsal attention network (DAN) and the right superior frontal gyrus and decreased rsFC with the right supramarginal gyrus (pFDR < 0.05) that was driven by differences between contact and collision groups at pre-season.

Conclusions: Differences identified over the course of a season of play indicate largely decreased rsFC within the DMN, which may have been driven by rsFC changes in contact athletes, consistent with prior literature. Additionally, we observed that level of contact was associated with differences in rsFC of the DAN in female varsity athletes. The association between exposure to repetitive head impacts (RHIs) and observed changes in network rsFC supplements the growing literature suggesting that even non-concussed athletes may be at risk for changes in brain functioning. However, the complexity of examining the direct effects of RHIs highlights the need to consider multiple factors including mental health and sport specific training and expertise, which may potentially be associated with neural changes.

Keywords

Functional connectivity, repetitive head impact, contact sports, female athletes

DEDICATION

This thesis is dedicated to my husband, who has made many sacrifices so that I could follow my dreams. It is also dedicated to my parents, who have been my unwavering supporters in all of life's adventures, including this one.

ACKNOWLEDGMENTS

The completion of this thesis would not have been possible without the assistance of many people. Their contributions are sincerely appreciated and gratefully acknowledged. I would like to specifically express my appreciation to Dr. Magdalena Wojtowicz for her guidance in this project and continuous encouragement which pushed me to mature as a researcher. I would also like to thank Dr. Dale Stevens, who offered his expertise to this project and consistently challenged me to learn and expand my skills, and Dr. Diana Gobert for her assistance in helping me explore additional neuroimaging methods.

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INTRODUCTION

Athletes who engage in contact and collision sports are exposed to repetitive head impacts (RHIs) that are associated with rapid changes in head velocity due to a direct contact to the head or collision to the body (Dashnaw et al., 2012). These impacts often lack visible signs of injury and/or may result in subthreshold clinical symptoms in comparison with hits resulting in concussion(s) (Shaw, 2002). However, there is a growing literature examining potential cumulative effects of RHIs on athletes' physical, cognitive, and emotional health (Bailes et al., 2013; Hwang et al., 2017; McAllister et al., 2012; Talavage et al., 2014). To date, studies examining the possible cognitive effects of RHIs have revealed mixed findings. Several studies have identified decreases in neurocognitive performance over the course of an athletic season associated with sport exposure in the absence of reported concussions (Breedlove et al., 2012; Davenport et al., 2014; McAllister et al., 2012; Talavage et al., 2014). These studies reported differences in performance on measures of visual working memory, verbal memory (Breedlove et al., 2012; Talavage et al., 2014), reaction time (McAllister et al., 2012), learning (McAllister et al., 2012), and goal-driven behaviour (Zhang et al., 2013). In contrast, other studies have not observed such differences over the course of a season (Gysland et al., 2012; Miller et al., 2007).

The available research examining evidence of differences in structural brain metrics associated with RHIs has also reported mixed findings. Some studies have not observed white matter or cortical volume differences over the course of a season in collision athletes (Mayinger et al., 2018; Slobounov et al., 2017). However, others have reported changes in multiple structural metrics in both short-term (Sollmann et al., 2018) and long-term findings (Koerte et al., 2016), as well as differences between collision and noncontact athletes at baseline (Churchill et al., 2017; Manning et al., 2020).

Using fMRI, several studies have identified changes to resting-state functional connectivity (rsFC) following exposure to RHIs (Abbas et al., 2014, 2015; Breedlove et al., 2012; Churchill et al., 2017; Johnson et al., 2014; Manning et al., 2020; Monroe et al., 2020; Slobounov et al., 2017; Talavage et al., 2014). RsFC measures correlations of spontaneous fluctuations in blood oxygenation level-dependent (BOLD) signal, which reflects neural vascular coupling associated with covarying neural activity across brain regions, and may detect subtle changes in the neural integrity of brain regions and networks which may be vulnerable to head impacts (Biswal et al., 1995; Raichle, 1998). Resting state networks reflect connectivity beyond what is expected from structural connectivity and consistent organization of rsFC is found across and within individuals. Functional networks reflect cognitive processing and may play a dynamic causal role in cognition. (Stevens & Spreng, 2014). Across brain regions, rsFC may and detect subtle changes in the neural integrity of brain regions and networks which may be vulnerable to head impacts (Biswal et al., 1995; Raichle, 1998). Research on male football athletes has revealed differences in rsFC among asymptomatic football players over the course of season (Abbas et al., 2014, 2015; Breedlove et al., 2012; Slobounov et al., 2017). These studies have consistently observed hyperconnectivity within the default mode network (DMN; Abbas et al., 2014, 2015) and rsFC differences between seeded regions of the DMN (i.e., cingulate cortex, and hippocampus) and regions throughout the rest of the brain (Slobounov et al., 2017). Collegiate rugby players scanned before and after a single game showed increased connectivity between orbitofrontal cortices and the left supramarginal gyrus, as well as decreased connectivity between the right retrosplenial cingulate cortex and the right posterior cingulate cortex (Johnson et al., 2014). In male soccer players, rsFC increases in the central autonomic network have been observed in association with the amount of head-to-ball impact exposure over a season (Monroe et al., 2020). Differences in rsFC between athletes have also been observed at baseline. For example, Churchill and colleagues (2017) examined varsity athletes involved in various levels of contact and collision sports and reported the highest global connectivity in non-contact athletes, and lowest global connectivity measures in collision athletes; suggesting potential better functional neural integrity in lower contact athletes.

The majority of the literature examining RHIs has focused on male football players (i.e., total number of imaging studies examining RHIs = 12, number of studies including both males and females = 3, number of studies including only females =1; See Table 1 for a summary of findings from an in-depth literature review). Despite accounting for 43% of the collegiate athlete population (Irick, 2015), female athletes have been severely understudied in this literature. The type of impacts that female athletes sustain may be different than their male counterparts, due, in part, to smaller neck size and differences in type of play (Abrahams et al., 2014; Tracey Covassin et al., 2003; Delaney et al., 2002; Gessel et al., 2007; Marar et al., 2012). In addition, some studies examining outcomes following concussion in female athletes have found that females report experiencing more adverse symptoms (Broshek et al., 2005; Zuckerman et al., 2014), greater symptoms of depression (Fenton et al., 1993), and worse neurocognitive performance (Broshek et al., 2005; Covassin et al., 2007; Majerske et al., 2008; Sollmann et al., 2018). Females showed a different pattern of cognitive performance with greater impairment on tests of visual memory (Covassin et al., 2007), reaction times, and visual motor speed (Broshek et al., 2005; Majerske et al., 2008; Sollmann et al., 2018a). Conversely, females performed better on verbal memory scores than male athletes (Covassin et al., 2006).Additionally, female athletes tend to have a longer recovery process, demonstrating that recovery is not uniform across sexes (Covassin & Elbin, 2011; Zuckerman et al., 2014) despite literature suggesting potential neuroprotective effects of female sex hormones such as estrogen and progesterone (Behl, 2002; Djebaili et al., 2005). This raises questions regarding potential sex-related differences in outcomes following RHIs. Few studies have examined neural differences in female athletes associated with RHI. One study reported decreased white matter microstructure integrity after a season of play in female hockey players but not male hockey players (Sollmann et al., 2018). Another recent study reported differences in white matter microstructure and rsFC between female rugby athletes and females involved in noncontact sports, in addition to longitudinal changes between in- and off-season (Manning et al., 2020).

The purpose of this study was to examine cognitive and neural functioning of a cohort of female varsity athletes over the course of a season of play. Specifically, I examined changes in rsFC within the DMN, sensorimotor (SMN), frontoparietal (FPN), dorsal attention (DAN), and salience (SN) networks post-season compared to pre-season in female athletes involved in collision and contact sports (i.e., volleyball, soccer, basketball, ice hockey, and field hockey). Furthermore, I examined whether there were rsFC differences in these networks associated with level of contact (i.e., collision versus contact). Mental health factors including depression and anxiety were also included as these factors have been shown to correlate with rsFC, specifically within the DMN (Sheline et al., 2009; Zhao et al., 2007). This study hypothesized that there would be 1) differences in rsFC between contact and collision athletes and that 2) there would be changes in rsFC over the course of a season, and that these changes would be different in contact athletes compared to collision athletes.

METHODS

Participants

Female university athletes involved in ice and field hockey, basketball, soccer, and volleyball were recruited from York University. Participants were eligible if: i) they were over 18-years-old, ii) were rostered to play on a university team for the current season, and iii) met the requirements for safe MRI scanning. In the pre-season condition, 31 female varsity athletes from York University, Toronto, between the ages of 18 and 21 years (*M* = 19 years 9 months, *SD* = 1 year 6 months). Average age at first sport was six years (*M* = 6 years 1 month, *SD* = 2 years 10 months). Participants were involved in collision (ice hockey, field hockey; N = 15) and contact (volleyball, soccer, and basketball; N = 16) sports. Level of contact was determined in accordance with the classifications proposed by Rice (2008), determined by estimating the level of relative risk for an acute injury. Collision suggests greater risk of injury, where athletes purposely come into rough contact with other players or objects, and the contact sports classification incudes players who often come into contact with each other as a by-product of the sport and with less force.

A subset of participants tested at pre-season were included at follow-up. Participants (N = 19) were female varsity athletes from York University, Toronto, between the ages of 18 and 21 years (*M* = 19 years 7 months, *SD* = 1 year 2 months). Participants were involved in collision (N = 12) and contact (N = 7) sports. Average age at first sport was five years (*M* = 5 years 6 months, *SD* = 2 years 7 months). These 19 participants were used in the following analyses.

Procedure

This study was approved by the Human Participants Review Sub-Committee of York University's Ethics Review Board. Participants provided written informed consent to complete the imaging and behavioral components of the study. Participants completed two scanning sessions when structural and functional images were collected: one before the start of their athletic season and one following their athletic season. Participants also completed questionnaires and were compensated $50 for their time.

Measures

Patient Health Questionnaire-9 (PHQ-9). The PHQ-9 (Kroenke & Spitzer, 2002) is a 9-item questionnaire of self-reported symptoms of depression. Participant total depression severity score is calculated by summing the items; total scores of 5, 10, 15, and 20 represent mild, moderate, moderately severe, and severe depression, respectively.

Generalized Anxiety Disorder-7 item (GAD-7). The GAD-7 (Spitzer et al., 2006) is a well validated, 7-item questionnaire to assess self-reported anxiety. Total score cut-offs of 5, 10, and 15, represent mild, moderate, and severe anxiety, respectively

Sport Concussion Assessment Tool-5 (SCAT5). The SCAT5 (McCrory et al., 2005) was used to assess concussion symptoms by using scores from the Standardized Assessment of Concussion (SAC) and the Post-Concussion Symptom Scale (PCSS).

Substance use. Substance use habits were recorded using the Alcohol Use Disorder Identification Test-Clinical (AUDIT-C) screening index (Babor et al., 2001). Cannabis use was measured using a health questionnaire asking the question, "how often do you smoke marijuana?". Possible responses to this question were never, monthly or less, 2-4 times a month, 2-3 times per week, 4+ times per week.

Attention network test (ANT-I). The ANT-I is a brief task of attention task and executive control that uses 2 (alerting) x 3 (orienting) x 2 (executive) design. Twenty-five practice trials (with visual feedback for correct and incorrect responses) are followed by 288 test trials (without feedback) in which stimuli are presented at intervals varying from 400 to 1600 ms. Participants are presented with a fixation cross in the middle of a computer screen on each trial. The alerting stimulus is a 50 ms, 2000 Hz tone that follows the inter-stimulus interval on half of the trials. The orienting cue is an asterisk that is presented on the screen for 50 ms, on 2/3 of the trials. This occurs 100 ms after the alerting tone or the period of time when the tone would have been presented. Ninety-six of the trials are preceded by a ‘‘valid’’ spatial cue in which the asterisk appears in the location where the target stimulus will subsequently appear. Another 96 trials are preceded by an ‘‘invalid’’ cue, in which the asterisk is presented at the same distance from the central fixation cross, but in the opposite direction as the eventual target location (e.g., above rather than below the fixation cross). No cue is presented on the remaining 96 ‘‘no cue’’ trials. The target stimulus on every trial is an arrow that appears either above or below the fixation cross. The participant’s task is to identify its direction by pressing either the ‘‘/’’ key for a right-pointing arrow or the ‘‘z’’ key for a left-pointing arrow on the computer keyboard. The executive (or ‘‘congruency’’) condition is manipulated by surrounding the target arrow with two arrows of equal size on each side. These ‘‘flanker’’ arrows point either in the same (congruent) or the opposite (incongruent) direction as the target. Half of the trials present congruent flankers while on the other half the flankers are incongruent with the target direction.

MRI acquisition. MRI data were acquired using a 3T Siemens TRIO MRI scanner (Siemens, Erlangen, Germany). Images were acquired for each subject before the beginning of the season and following the season. Whole brain, high-resolution, T1-weighted anatomical scans were collected using an ascending multi-slice 3D Magnetization Prepared Rapid Acquisition Gradient Echo (MP-RAGE) sequence (FOV = 256 mm, 1.0 x 1.0 x 1.0 mm voxels, TR = 2300, TE =2.62 ms). Acquisition time was 5 minutes, 21 seconds. To study brain function, a whole brain multi-echo planar imaging (EPI) sequence (T2*-weighted) was used to acquire functional data in 240 volumes (43 slices, FOV = 216 mm, 64 x 64 matrix, 3.4 x 3.4 x 3.0 mm3 voxels, TR = 3000 ms, echo times [TEs] = 14 ms, 30 ms, 46 ms, flip angle = 83°). Acquisition time was 12 minutes. During fMRI scanning, patients lay still with their eyes closed.

Functional imaging preprocessing

Using CONN toolbox Version 18.b (Whitfield-Gabrieli & Nieto-castanon, 2012) on the Matlab Version R2019a platform, fMRI data (i.e., the second echo from the multi-echo scan) were preprocessed. The default preprocessing pipeline was used and functional data were functionally realigned and unwarped, translated by centering to (0,0,0) coordinates, slice-time corrected, scrubbed with ART-based identification for outlier scans, segmented into grey matter (GM), white matter (WM), and cerebrospinal fluid (CSF), normalized to the Montreal Neurological Institute (MNI) template MNI152, and smoothed using an 8 mm Gaussian kernel, full width at half maximum. Denoising was performed using linear regression of the following nuisance parameters: 1) Realignment parameters (n = 12): 6 realignment parameters (three translational and three rotational) as well as the first temporal derivative of each; 2) Condition effect (n = 2): constant and linear BOLD signal within each session to reduce the influence of slow trends and/or initial magnitization transience in the BOLD signal; 3) Spike regression (n = 0-15): one regressor for each outlier time-point (n-range = 0-15 across participants) in the time-series; 4) White matter signal (n = 5): 5 temporal principal components; and 5) Cerebral spinal fluid (n = 5): 5 temporal principal components. Mean global signal regression was not performed in light of the potentially detrimental effects which have been debated in recent literature (Gotts et al., 2013, 2020; Murphy et al., 2009; Saad et al., 2012; Spreng et al., 2019). Finally, data were linearly de-trended and default band-pass filtered (0.008-0.09 Hz). Quality assurance plots were produced to indicate number of valid scans, max and mean motion, and max and mean global signal change for each subject.

Independent Component Analysis

Using a whole brain, multivariate approach, rsFC data were analyzed with the independent component analysis (ICA) pipeline in CONN toolbox (Whitfield-Gabrieli & Nieto-castanon, 2012). Default settings were employed by temporally concatenating across subjects and using group-level dimensionality reduction and FastICA to estimate 20 independent spatial components. The group independent analysis setting (GICA1) was used to back-project using dual regression with multivariate spatial-regression and multivariate temporal-regression for individual subject-level spatial map estimation. The default subject-level dimensionality reduction value of 64 (number of components kept when characterizing the voxel-to-voxel correlation matrix separately for each subject) was used. Spatial match-to-template correlations between each group-level spatial map and the CONN toolbox pre-defined networks based on Harvard-Oxford and Automated Anatomical Labeling (AAL) atlases were used to identify resting-state networks. Highly correlated components were visually verified and selected by the experimenter (See Appendix B). Specific networks were chosen based on involvement in clinical symptoms associated with RHIs. Networks of interest including the DMN, SMN, FPN, DAN, and SN were used in second-level analyses (See Figure 1).

Statistical analysis

Clinical variables. Variables were examined for normality and univariate outliers; there were no major violations of assumptions and therefore, parametric tests were used. Independent t-tests were run on pre-season data to compare age, age at first sport, concussion history (number of previous concussions), GAD-7 total score, PHQ-9 (total score), SCAT total number of symptoms, SAC subtotal, and AUDIT-C total score, in contact versus collision groups. A chi square analysis was performed to compare the number of marijuana users in each group. Two-tailed alpha values of less than .05 were considered statistically significant. Paired samples t-tests were run between pre-season and post-season scores for all athletes assessed at both timepoints.

ANT-I analysis. Participants with >80% accuracy on the 288 trails were included in the analysis (total n =19). Mean reaction times were calculated for each participant across trials as well as intra-individual variability using the individual standard deviations (ISD; Wojtowicz et al., 2014) to measure stability of performance across trials, which were both compared in a repeated measures ANOVA. Alerting, orienting, and executive scores were also calculated by aggregating performance on the trials specific to each domain, which were run in a repeated measures ANOVA. Twelve condition scores were calculated, one for every combination of alerting (tone vs. no tone), orienting (valid, invalid, or no cue) and executive control (congruent vs. incongruent flankers) factors which were compared across the conditions of group (level of contact) and time (pre- vs post-season) in a 2x3x2x2x2 repeated measures ANOVA. Repeated measure ANOVAs for group and time were performed for ISD. The Statistical Package for the Social Sciences (SPSS) version 24 (IBM corp., 2016) was used for all analyses. For all analyses, two-tailed alpha values of less than .05 were considered statistically significant.

fMRI analysis. To investigate the effect of level of contact, a 2x2 analysis of variance was used. We analyzed the main effects of group (contact and collision) and time (pre-season and post-season) as well as the group x time interaction. We performed a follow-up analysis for the main effect of time in significant ICA components with two within-subject t-tests contrasting contact sport athletes at pre- and post-season and contrasting collision sport athletes at pre- and post-season. We also performed a follow-up analysis for the main effect of group using between-subject t-tests contrasting contact and collision sport athletes at pre-season and again at post-season. Non-parametric tests were used with an uncorrected voxel threshold of $p < 0.001$ and a cluster-mass correction of $p < 0.05$ FDR.

RESULTS

Participant characteristics

At pre-season, there were no significant differences in age, age at first sport, concussion history, SAC symptoms, alcohol use, and number of marijuana users between contact and collision athletes (ps > .05; See Table 2). Contact athletes, however, did have significantly higher PHQ-9, GAD-7, and total SCAT symptom scores (see Table 2). There were no significant differences in clinical scores between pre-season and post-season scores (ps > .05; See Table 2).

ANT-I results

ANT-I results are presented in Table 3. Overall scores showed within-subject effects of the alerting, orienting, and executive function networks [Alerting: $F(1,17) = 5.66$, $p = .029$; Orienting: $F(2,34) = 86.03$, $p < .001$; Executive: $F(1,17) = 527.96$, $p < .001$]. Post-hoc analyses revealed that participants responded more quickly when there was a tone, valid cue, or congruent flanker in the alert, orient, and executive conditions respectively (ps < .05). There were no between-subject effects [$F(1,17) = 2.66$, $p = .121$]. There was also a significant main effect of time ($F(1,17) = 6.91$, $p = .018$; partial eta squared = 0.29) but no main effect of group ($F(1,17) = 2.66$, $p = .121$, partial eta squared = 0.14). In a post-hoc analysis of time, post-season was faster than pre-season ($p <0.05$). A repeated measures ANOVA of ISD did not show significant effects of time ($F(1,17) = 2.47$, $p = 0.625$, partial eta squared = 0.014) or group ($F(1,17) = 1.297$, $p = 0.270$, partial eta squared = 0.071).

Resting-state functional connectivity results

There was a main effect of time in the DMN (See Figure 2) that showed decreased rsFC at post-season with a relatively large cluster primarily in superior parietal lobule, with some voxels in the superior division of the lateral occipital cortex and spreading into the precuneus and postcentral gyrus in the right hemisphere (T = -6.85, pFDR = .001), and a cluster across the supramarginal gyri and postcentral gyrus bilaterally (left, T = -6.13, pFDR = .004; right, T = -6.41, pFDR = .043). Another cluster primarily in the left superior frontal gyrus with spread into the precentral gyrus (T = -7.61, pFDR =.006) and one primarily in the superior parietal gyrus and lateral occipital cortex (T = -5.82, pFDR = .043) also showed decreased rsFC at post-season. Increased rsFC with the DMN was observed with a cluster in the right frontal pole (T = 6.27, pFDR = .043) at post-season. A Follow-up within-subject t-test analyses showed significant decreased rsFC between the DMN and three clusters bilaterally in the lateral occipital cortex (right, T = -19.32, pFDR = .001; right, T = -10.18, pFDR = .003; left, T = -16.42, pFDR = .003), left supramarginal gyrus (T = -27.85, pFDR =.001), left superior frontal gyrus (T = -13.75, pFDR =.003), bilateral superior parietal lobules (left, T = -12.81, pFDR = .010; right, T = -11.03, pFDR = .045) and right precentral gyrus (T = -10.08, pFDR = .045) in the contact group at post-season versus pre-season. No significant rsFC differences were observed between the DMN and other brain regions in a within-subjects t-test of the collision group at pre-season versus post season (See Table 4).

We observed a main effect of group in the DAN (See Figure 3) where collision sport athletes showed increased rsFC with a cluster primarily in the right superior frontal gyrus and spread into the left superior frontal gyrus and paracingulate gyrus (T = 7.33, pFDR = .035) and decreased connectivity with the right supramarginal gyrus (T = -6.09, pFDR = .037). To examine this in more detail, we ran follow-up analyses. A between-subjects t-test collision group and contact group at preseason showed increased rsFC between the DAN and a cluster primarily in the right superior frontal gyrus (T = 6.43, pFDR = .021) and decreased rsFC with a cluster in the right supramarginal gyrus (T = -5.15, pFDR = .044). No significant rsFC differences were observed between the DAN and other brain regions in a between-subjects t-test of the collision group and contact group at post season (See Table 4).

There was no significant group by time interaction.

DISCUSSION

Due to the growing concern regarding the effects of exposure to RHI, this study investigated pre- and post-season differences in cognition, emotion, and brain functional integrity in contact and collision female varsity athletes. Using the ANT-I we did not observe differences in attentional and executive control performance between groups; however, there was a reduction in overall mean RT at post-season. Prior studies examining reliability and stability of the ANT-I have reported that even following repeat test administration, the network scores remained generally stable and robust, with some evidence of practice effects primarily in the executive network (Ishigami et al., 2013; Ishigami & Klein, 2011). The reduction in overall mean RT between the two sessions in our study may reflect a practice effect related to the ANT-I or may alternatively reflect specific training exposure associated with sport participation over the course of a season. When examining clinical variables including depression, anxiety, and concussion assessment symptoms, we did not observe significant differences between pre- and post-season assessments, although it is notable that contact athletes displayed significantly higher symptom scores in all three measures compared to collision athletes at baseline.

Several studies have highlighted changes in the DMN following a season of play related to level of contact exposure in athletes (Abbas et al., 2014, 2015; Johnson et al., 2014; Manning et al., 2020; Slobounov et al., 2017). The DMN is a network involved in meditative and self-reflective processing (Raichle et al., 2001) that has been shown to support goal-directed cognition when coupled with the frontoparietal network (Spreng et al., 2010). It has also been associated with internally focused cognitive processes such as mind-wandering, self-referential thought, memory recollection, future planning, and social cognition, among others (Spreng, 2012). Studies have shown that non-collision sport athletes displayed a consistent number of DMN connections between pre- and post-season scans whereas collision sport athletes have shown variability in the rsFC of the DMN throughout the season (Abbas et al., 2014, 2015). Other studies have reported greater DMN connectivity in higher contact level athletes compared to non-contact athletes throughout the season (Manning et al., 2020) and in a study of football players, those who experienced a larger number of high impact hits showed greater increases in DMN rsFC (Slobounov et al., 2017). However, in the former study, no differences in DMN connectivity were observed in players with no prior history of concussion, suggesting that there may be a certain vulnerability to exposure to repetitive head impacts in players with prior concussions (Manning et al., 2020). It is striking that out of all the networks, our primary rsFC finding supports the current literature, showing changes between DMN rsFC and other brain regions following a season of play, suggesting that this finding is relevant and is likely not attributable to noise. In a comparison of pre- and post-season fMRI data, we observed decreased connectivity between the DMN and occipital, supramarginal, superior frontal, and superior parietal brain regions, and an increase in connectivity with the frontal pole in post-season scans. Follow-up t-test analyses revealed decreases in rsFC between the DMN and other brain regions following a season of play in contact sport athletes but did not show any changes between pre-season and post-season in collision sport athletes. Prior research has reported rsFC differences at baseline between athletes engaged in various levels of contact sport (Churchill et al., 2017), with the most robust differences observed between collision and non-contact athletes. Our study suggests that there may also be changes in functional connectivity associated levels of exposure to head injury. However, it is notable that our sample was relatively small and we did not include additional measurement of RHIs, thus the observed changes may be attributable to a number of additional factors such as differences in training received by playing different sports, the number of practices and games, as well as differences in baseline depression and anxiety symptoms.

To further explore potential baseline differences between groups, we examined rsFC between contact and collision athletes at pre-season. We observed rsFC differences between the DAN and other brain regions that included increased rsFC with the superior frontal gyrus and decreased rsFC with the supramarginal gyrus in collision sport athletes compared to contact sport athletes. This difference may represent distinctions in specialized sport-specific attentional requirements; however, there were no group differences in altering, orienting, or executive control, components of the ANT-I. There were also no significant differences in mean concussion history between contact and collision groups in our sample and the ranges of lifetime concussions in both groups were similar (i.e., between 0 and 4 in contact players and 0 and 3 in collision players). Other literature has shown that differences in rsFC may reflect neuroplasticity required for expertise development associated with different sport requirements (Chang et al., 2018) and for specific relevant abilities such as motor skill learning (Dayan & Cohen, 2011). The demands of different sports require specialized skills of the athletes playing them, such as various adaptations to different sport surfaces. For example, hockey requires athletes to play on ice versus other sports are played on a field or court. Additionally, some athletes require techniques using equipment that is an extension of the body rather than simply the body itself. Another consideration is that our contact group was composed of athletes that played a larger variety of sports compared to the collision group, which may complicate the interpretation of the pre-season differences observed in the DAN. Additionally, no group by time interaction was observed, however this could be due to unequal group sizes included in this study.

This study has several limitations that need to be addressed. First, this study has a small sample size of female athletes competing at the university level, although it is notable that our sample is comparable to other neuroimaging studies examining changes in athlete functions associated with exposure to RHIs (Abbas et al., 2015; Breedlove et al., 2012; Johnson et al., 2014; Koerte et al., 2016; Mayinger et al., 2018; Monroe et al., 2020; Slobounov et al., 2017; Sollmann et al., 2018; Talavage et al., 2014). As shown in the scoping review (see Table 1), 10 of the 12 studies include sample sizes between 10 to 30 participants. Another limitation is the lack of accelerometry data and/or observable measurement for RHIs to quantify the number and severity of the hits. Although objective measures of RHIs are necessary, some studies have noted discrepancies between RHIs identified by accelerometry and video review (e.g. (Press & Rowson, 2017), and data collected by telemetry systems have been known to overestimate linear and rotational acceleration (Beckwith et al., 2012; Cobb et al., 2013; Young et al., 2014). This highlights the need for the development of more accurate measurements of head impacts. In addition, some variables of interest were assessed using self-reported measures (e.g., mental health and substance use screeners) and there is the possibility of response bias from participants who may have concerns about their team eligibility in answering questions truthfully. To minimize this effect, researchers emphasized that players answers were confidential and not used in the pre-season play decisions.

Despite a small sample size and other limitations, this study addresses important gaps in the literature by examining functional neuroimaging correlates of contact exposure using a network-level approach as opposed to examining single networks (e.g., DMN solely) or using seed-based approaches. In addition, this study represents one of the few to examine rsFC associated with contact exposure in exclusively female athletes (Manning et al., 2020). The one prior study examining rsFC in female athletes reported that concussion-free contact sport athletes during both in- and off-season assessments showed greater connectivity between the DMN and the posterior cingulate cortex compared to non-contact athletes (Manning et al., 2020). Similarly, in our study the lower contact group showed reduced connectivity between the DMN and other brain regions, even within a relatively small female sample. Further, despite using a broad network approach, our study identified observable differences in the DMN following a season of play, emphasizing the robust nature of associations between contact exposure and DMN, specifically.

CONCLUSION

Results of this study suggest that changes in rsFC across neural networks can occur over the course of a season in female varsity athletes. Specifically, our findings suggested network differences between collision and contact athletes which may be driven by pre-season differences potentially as a result of inherent difference in sport requirements. Changes were also seen in a pre- and post-season analysis which revealed decreases in rsFC between the DMN and other brain regions in post-season scans. These findings highlight the complexity of examining changes directly associated with RHIs and emphasize the need for considering multiple factors (e.g., pre-season and sport differences) that might be associated with cognitive and neural changes observed over the course of a season, beyond just the suspected effects of RHIs.

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Table 1. Literature table.

Lead Author and Study Year	PMID	Modality	Sample size (M:F)	Age: mean (SD)	Sport	Level of Competition
Abbas et al., 2014	25242171	Seed-based fMRI of DMN	32 (32:0)	Collision: 22 (16.7 yrs, range: 14-18 yrs) Non-contact: 10 (16.7 yrs, range: 14-18 yrs)	Football, Tennis, Cross-country, Golf, Baseball, Swimming	High School
Aim of Study: To examine changes in the DMN after repetitive subconcussive mild traumatic brain injury. **Concussion Criteria:** NR; **Diagnosis:** Athletic trainer, Team physician; **Post- Concussion Symptoms**: NR **Accelerometry, neuropsychological or psychological data:** Head impact telemetry for football. (collected but not used or reported). **Neuroimaging Acquisition, Post-processing, & Analysis:** 3T General Electric Signa HDx, 16-channel brain array. Gradient-echo echo-planar sequence, scan length 5 min 30 sec; repetition time (TR) 1500 ms; echo time (TE) 26 ms; flip angle 35°; 34 slices at 3.8 mm; field of view 20 cm; 64 · 64 acquisition, resulting in 3.125mm· 3.125mm in-plane resolution). T1-weighted anatomical, three-dimensional spoiled gradient-recalled echo sequence (TR 5.768 ms; TE 2.032 ms; flip angle 73°; 0.9375mm· 0.9375mm· 1 mm). Analysis of Functional NeuroImages and FMRIB Software Library: preprocessing pipeline implemented where localized white matter regressors were extracted and used to implement a reduced version of the ANATICOR, which results in minimal sensitivity to motion and dependence of correlation results on censoring. Volumes associated with movement of 0.4mm or greater were censored from the regression. ROI-based correlational Analyses: Automated Anatomical Labeling atlas using the labels of Tzourio-Mazoyer divided brain into 116 ROIs. A seed region was defined by a 12mm radius spherical ROI placed at the posterior cingulate/precuneus (Talairach -5,49,40). Bivariate correlations were used as a reflection of connection between ROI pairs. Each of the 116 ROIs were considered as possible connections to the seed ROI. Non-contact athletes scanned at baseline and follow up. Collision athletes scanned 3-6 times at pre-season, at least one in-season, and post-season. For each session, ROI analyses were performed with a GLM to determine significant rsfMRI DMN connections at the individual level. Changes in the number DMN connections across sessions were evaluated in the collision-sport athletes for possible relationship to exposure to collision events by comparing each session relative to its preceding session, and by comparing each session relative to the Pre-Season session. Changes in DMN connections across consecutive sessions were evaluated using a combinatorial analysis **Primary Neuroimaging Findings:** Baseline and follow-up sessions of non-collision-sport controls had no significantly different DMN connections between the two sessions. Collision-sport athletes showed higher numbers of significant DMN connections than non-collision-sport athletes for Pre-Season, Month-2, Month-3, and Post-Season sessions, but lower or comparable number of DMN connections for Month-1 and Month-4 sessions. At Pre-Season, Month-2, Month-3, and Post-Season, collision-sport athletes exhibited a higher (but not necessarily significantly higher) median number of DMN connections than the non-collision-sport controls. Conversely, collision-sport athletes exhibited a lower (but not necessarily significantly lower) number of DMN connections relative to their non- collision peers at Month-1 and Month-4.						

Participants' information included demographics and fight exposure, cognitive testing, neurologic examination, psychiatric symptom scales, a blood draw for genetic analysis, and a 3 T magnetic resonance imaging (MRI) scan with structural and functional sequences (main outcomes: volumes of the hippocampus, amygdala, caudate, putamen, and thalamus, and the anterior, central, and posterior corpus callosum).
Secondary Neuroimaging Findings: The number of DMN connections exhibited greater variability across session for the collision-sport athletes.

Lead Author and Study Year	PMID	Modality	Sample size (M:F)	Age: mean (SD)	Sport	Level of Competition
Abbas et al., 2015	25649781	Seed-based fMRI of DMN	10 (10:0)	17 yrs, range:16-18 yrs	Football	Highschool

Aim of Study: To examine changes in DMN connectivity for clinically asymptomatic high school football athletes
Concussion Criteria: NR; **Diagnosis:** Athletic trainer, Team physician; **Post- Concussion Symptoms**: NR
Accelerometry, neuropsychological or psychological data: N/R
Neuroimaging Acquisition, Post-processing, & Analysis: 3T Signa HDx (General Electric), 16- channel brain array. Gradient-echo echo-planar sequence (scan length 9 min 46 sec; TR 2,000 msec; TE 26 msec; flip angle 35°; 34 slices at 3.8 mm; FOV 20 cm; 64 × 64 acquisition). T1-weighted anatomical was acquired for registration purposes (1 mm isotropic resolution). Data were preprocessed using a pipeline based on Jo et al. (2013). Correlational analysis was performed on a ROI basis. The Automatic Anatomical Labeling (AAL) atlas divided the brain into 116 ROIs. A seed region was defined by a 12 mm radius spherical ROI placed at posterior cingulate/precuneus (Talairach –5,49,40). Connectivity to this node was further analyzed as a proxy to DMN connectivity. Bivariate correlations were used as a reflection of connection between ROI pairs. A GLM was performed to determine significant rsfMRI DMN connections at the individual level. Athletes participated in nine imaging sessions; one prior to the start of contact practices (Pre-Season), two during the competition schedule (In-Season; completed within 48 hours of a game or practice), and six after the end of season (Post-Season). In-Season sessions were grouped into two month-long windows (Month-1 and Month-2). Post-Season sessions, grouped into six month-long windows (Post-1 to Post-6). During the five months of Post-Season scanning, all football athletes played another sport
Primary Neuroimaging Findings: The number of DMN connections exhibited marked variability across session for collision-sport athletes. DMN connections observed during the in-season scans were significantly reduced at Month-1, and significantly increased at Month-2. Post-season DMN connections were significantly reduced at all sessions except the December measurement.
Secondary Neuroimaging Findings: N/R

Lead Author and Study Year	PMID	Modality	Sample size (M:F)	Age: mean (SD)	Sport	Level of Competition
Breedlove et al., 2012	22381736	Task-based fMRI	24 (24:0)	17 yrs, range: 15-18 yrs	Football	Highschool

Aim of Study: To examine how the head collision histories of the athletes correlate with the observed changes in their neurophysiology.

Concussion Criteria: NR; **Diagnosis:** Clinician; **Post- Concussion Symptoms**: Clinically-observed impairment (COI) and functionally-observed impairment (FOI)— detected using neuropsychological testing and fMRI. Probed 6 components of cognitive function: attention span, working memory, sustained and selective attention time, response variability, non-verbal problem solving, and reaction time. **Accelerometry, neuropsychological or psychological data:** Head Impact Telemetry **Neuroimaging Acquisition, Post-processing, & Analysis:** 3T General Electric Signa HDx,16-channel brain array. Whole-brain high-resolution images (3D-FSPGR; 1mm isotropic resolution) were acquired, including the cerebellum. Three functional runs were conducted of a visual working memory (N-back) paradigm, using gradient-echo echo planar imaging (TR/TE = 1500/26 msec; matrix = 64 · 64; FOV= 20 cm; 34 slices; 3.8mm thickness; 117 volumes). In each run subjects performed one block (15 presentations, 3-sec interval, 5 targets per block) each of 0-, 1-, and 2-back tasks for single letters. Subjects responded by dominant index finger via fiberoptic button box. The order of the task blocks in the three runs was counter-balanced within each session, and across assessments. Using AFNI, working memory task conditions, were compared. 116 anatomical regions of interest (ROIs) were determined. A pre-season fMRI session was conducted before the start of contact practices. Follow-up tests were performed within 72 hours of contact activity in season 1 and within 48 hours for season 2. Individual with a diagnosed concussion is COI+/FOI+ (all of the individuals diagnosed with a concussion demonstrated functional impairment). Individuals with no diagnosed concussion and no functional impairment were COI-/FOI-. Individuals were defined as being COI-/FOI+ if they had no observable signs of concussion but nevertheless showed a statistically significant reduction in at least one of their visual composite score or verbal composite score categories for ImPACT. **Primary Neuroimaging Findings:** Of the 116 regions of interest (ROIs), 33 yielded significant regressions relating changes in fMRI to the blows sustained by the COI-/FOI- Group. 39 ROIs yielded significant regressions relating changes in fMRI to the blows sustained by the COI+/FOI+ group. The spatial distributions of the ROIs in the COI+/FOI+ and COI-/FOI- groups for which a significant regression was obtained indicate distinct regions of correlation. While some overlap exists in the frontal, cerebellar, and basal ganglia regions, the COI-/FOI- group exhibited a concentration of correlations in the upper parietal and occipital regions. in contrast, the COI+/FOI+ group exhibited an additional concentration of correlations in the temporal and lower parietal regions. **Secondary Neuroimaging Findings:** There was no significant difference in the median peak linear acceleration for any of the three groups, however, a significant difference in the median total number of blows was found. Subsequent pairwise tests indicated that the COI-/FOI+ group sustained more blows than the COI-/FOI- group. The number of side blows sustained by each of the groups was significantly different and pairwise tests indicated the COI-/FOI+ group sustained significantly more side blows than the COI+/FOI+ group. Scatterplots displaying a two-dimensional projection of recorded impact location and peak linear acceleration illustrated that the members of the COI-/ FOI+ group sustained a majority of their blows to the top-front region of the helmet, especially those above 80 G.						
Lead Author and Study Year	PMID	Modality	Sample size (M:F)	Age: mean (SD)	Sport	Level of Competition
Churchill et al., 2017	28878729	fMRI & DTI & Single-voxel spectroscopy	65 (32:33)	Collision: 23 (21.3 ±1.9 yrs) Contact control: 22 (20.3 ± 1.5 yrs)	Rugby, Ice hockey, Lacrosse, Football, Soccer, Field hockey, Basketball, Water polo, Volleyball	University

				Non-contact control: 20 (20.0 ± 1.7 yrs)		

Aim of Study: To evaluate multiple aspects of brain physiology in three groups of athletes participating.
Concussion Criteria: SCAT3 at pre-season; **Diagnosis:** In clinic; **Post- Concussion Symptoms**: NR
Accelerometry, neuropsychological or psychological data: N/R
Neuroimaging Acquisition, Post-processing, & Analysis: 3T Magnetom Skyra, Siemens, standard 20-channel head receiver coil. T1-weighted MPRAGE was obtained, with field of view (FOV) = 24 cm × 24 cm, 240 × 240 × 192 acquisition matrix, 0.9 mm isotropic voxels, bandwidth = 250 Hz/Pixel, inversion time (TI)/echo time (TE)/repetition time (TR) = 850/2.63/2,000 ms, and flip angle = 8o. FLAIR was obtained with FOV = 22 cm × 18.6 cm, 256 × 196 acquisition matrix, 1.1 mm × 0.9 mm × 3.0 mm voxels, TI/TE/TR = 2,200/96/9,000 ms. Susceptibility-weighted imaging was also acquired with 220 × 192 FOV, 0.6 mm × 0.6 mm × 1.2 mm voxels. TE/TR = 20/28 ms, flip angle = 15°, 384 × 307 with encoding gap of 0.2 mm. Diffusion-weighted imaging was acquired with 30 encoding directions (b = 700 s/mm2, FOV = 24 cm × 24 cm, 120 × 120 acquisition matrix, 66 axial slices, 2 mm isotropic voxels, TE/TR = 83/7,800 ms, bandwidth = 1,736 Hz/Px). The FSL1 eddy_correct protocol was used to perform simultaneous correction of eddy currents and rigid-body motion correction, bet was used to mask out non-brain voxels, and dtifit was used to calculate voxelwise measures of fractional anisotropy (FA) and mean diffusivity (MD). The individual subject FA and MD maps were co-registered to a common template space, based on the FSL FDT protocol. Multi-slice T2*-weighted echo planar imaging (FOV = 20 cm × 20 cm, 64 × 64 matrix, 32 slices, 3.125 mm × 3.125 mm × 4.5 mm voxels, TE/TR = 30/2,000 ms, flip angle = 70°, and oblique axial interleaved), producing a time series of 194 images. -Analysis of Functional Neuroimages (AFNI) and customized algorithms were used for processing Global FC (Gconn) was estimated for each voxel. Gconn was measured as the mean of all (positive) connectivity values, providing a voxelwise measure of total integrative function. Subsequent analyses compared the Gconn brain maps between the different sport groups. Single-voxel 1H spectroscopy data were acquired for two regions of interest, placed on left and right hand motor knobs. This was obtained via stimulated echo acquisition mode (STEAM) for 2 cm isotropic voxels (TM/TE/TR = 10/30/2,000 ms; bandwidth = 1,200 Hz; FA = 40°; 100 acquisitions; 1,024 points). Regions were placed on an AC-PC-oriented axial slice. Processing and analysis was conducted using the TARQUIN software package5with default preprocessing parameter settings for STEAM. N-acetyl aspartate (NAA), choline (Cho), creatine (Cr), and myo-inositol (Ins) were analyzed. All six unique pairwise ratios of the different metabolites were compared between sport groups. Mean-centered task PLS was used to identify patterns of brain voxels (FA, MD, and Gconn) or metabolite ratios that show covariation across the three sport groups (non-contact, contact, and collision).
Primary Neuroimaging Findings: Collision sports had higher FA than non- contact and contact sports, while non-contact and contact groups were not significantly different. Collision sports had lower MD than non-contact and contact sports while non-contact and contact were not significantly different. Gconn was highest for non-contact sports, intermediate for contact sports, and lowest collision sports. However, only collision and non-contact sports were significantly different after correcting for multiple comparisons, whereas contact sports could not be distinguished from either non-contact or collision sports. NAA/Cr ratios, showed progressive effects, with the highest values for non-contact sports, intermediate values for contact sports, and lowest values for collisions sports. Only the difference in NAA/Cr values between non-contact and collision sports was significant after correcting for multiple comparisons, while contact sports could not be distinguished from either non-contact or collision sports.

Secondary Neuroimaging Findings: There were no significant between-group differences for sex and prior concussion history. Pre-season symptom scores, total symptom severity was not significantly different between groups. Somatic complaints showed a significant difference between groups, with higher scores for collision sports compared to non-contact sports, although the effect was non-significant after adjusting for multiple comparisons. Cognitive and balance scores also showed no significant differences between groups. Combining all sport groups, FA within brain regions implicated in contact exposure and Gconn showed significant effects of concussion history, whereas MD and NAA/Cr ratio did not.

Lead Author and Study Year	PMID	Modality	Sample size (M:F)	Age: mean (SD)	Sport	Level of Competition
Johnson et al., 2014	25010992	Seed-based fMRI of DMN	24 (8:16)	Hx mTBI: 12 (20.5 yrs, range:19-23 yrs) No Hx mTBI: 12 (19.8yrs, range: 18-22 yrs)	Rugby	University

Aim of Study: To investigate the acute effects that subconcussive head trauma may have on the DMN.
Concussion Criteria: No participants reported concussive symptoms at scanning and no players were diagnosed with a concussion on the field; **Diagnosis:** Athletic trainer; **Post- Concussion Symptoms**: NR
Accelerometry, neuropsychological or psychological data: N/R
Neuroimaging Acquisition, Post-processing, & Analysis: 3T Siemens Trio,12-channel head coil. Two- dimensional BOLD echo planar rsfMRI sequence were acquired in the axial plane parallel to the anterior and posterior commissure axis covering the entire brain (3.0 x 3.0x 3.0mm resolution, TR= 2490ms, TE=24ms, iPAT=none, EPI factor =74, echo spacing= 0.48ms, NSA= 1, acquisition time= 5:04). Three-dimensional isotropic T1 weighted magnetization prepared rapid gradient echo anatomical images were acquired in the sagittal plane parallel with the longitudinal fissure covering the entire brain (1mm·1mm·1mm resolution, TE= 3.46 ms, TR=2300 ms, TI =900ms, flip angle =9°, 160 slices, iPAT=none, NSA= 1). Seed-based correlation analysis of the DMN was performed. Statistical Parametric Mapping (SPM) version 8 in conjunction with FC (CONN) toolbox were used for preprocessing and analysis. Seed ROIs of the DMN included dorsal frontal cortex, anterior prefrontal cortex, orbitofrontal cortex, medial prefrontal cortex, ventral posterior cingulate cortex, posterior cingulate cortex, precuneus, angular gyrus, retrosplenial cortex, and supramarginal gyrus. Pre-game scanning was performed 24 h prior to a full contact game. Post-game scanning was performed within 24 h of the end of that game. No sports-related subconcussive impacts were sustained between pre-game scanning and the actual game, as no contact practices were scheduled in the interim.
Primary Neuroimaging Findings: Pre-game/post-game differences in all subjects showed increased connectivity between left and right orbitofrontal cortices and the left supramarginal gyrus and decreased connectivity between the right retrosplenial cingulate cortex and the right dorsal posterior cingulate cortex. Hx mTBI demonstrated only reductions in FC following exposure to subconcussive head trauma. There was decreased connectivity from the left anterior prefrontal cortex and left right retrosplenial cingulate cortex, from the left inferior temporal gyrus to medial prefrontal cortex and between right ventral posterior cingulate cortex and left fusiform gyrus. No Hx mTBI group exhibited only increased connectivity from pre-game to post-game. The left supramarginal gyrus increased FC to the left and right orbitofrontal cortices and

between left retrosplenial cingulate cortex and right fusiform gyrus and between the left fusiform gyrus and medial prefrontal cortex. Hx mTBI cohort displayed significant decreases in FC, compared with the No Hx mTBI subgroup. Pre-game scans showed reduced FC between the left dorsal frontal cortex the left dorsal posterior cingulate cortex, right dorsal posterior cingulate cortex, and precuneus. Pre-game decreases were seen from the left supra- marginal gyrus to the left and right inferior temporal gyrus. Post-game analysis between subgroups revealed reduced connectivity from the left supramarginal gyrus to six other DMN ROIs: left and right anterior prefrontal cortices; left and right dorsal anterior cingulate cortices; right dorsal frontal cortex; and left inferior temporal gyrus. **Secondary Neuroimaging Findings:** N/R						
Lead Author and Study Year	PMID	Modality	Sample size (M:F)	Age: mean (SD)	Sport	Level of Competition
Koerte et al., 2016	26286826	Structural MRI	30 (30:0)	Contact: 15 (49.3 ± 5.1yrs) Non-contact:15 (49.6 ± 6.4 yrs)	Soccer, Running, Table tennis, Ballroom dancing	Former professional athletes
Aim of Study: To evaluate cortical thickness in former professional soccer players. **Concussion Criteria:** NR; **Diagnosis:** N/R; **Post- Concussion Symptoms**: NR **Accelerometry, neuropsychological or psychological data:** Neuropsychological tests: TMT, ROCF, BIS, BESS. Lifetime-estimate of headings **Neuroimaging Acquisition, Post-processing, & Analysis:** 3T MR Magnetom Verio, Siemens, 32-channel head coil array. T1-weighted 3D magnetization prepared rapid- acquisition gradient echo (MP-RAGE) acquired in a sagittal orientation and motion insensitive 3D T2-weighted BLADE sequence acquired in a transversal orientation. Imaging pa- rameters were as follows: MP-RAGE: TR = 1800 ms, TE = 3.06 ms, FOV = 256 mm, voxel size = 1 × 1 × 1 mm3, iPAT, acceleration factor 2; 3D T2-weighted BLADE se- quence: TR = 3000 ms, TE = 400 ms, FOV = 250 mm, voxel size =1×1×1mm3, slices = 160, iPAT, acceleration factor 2. Cortical thickness analysis was then performed using FreeSurfer version 5.3. The fully automated cortical reconstruction process was applied. Cognitive and behavioral measures were correlated with lifetime-estimate of heading. Group comparison of cortical thickness was performed. The effect of lifetime estimate of headings on cortical thickness was tested within the soccer cohort. **Primary Neuroimaging Findings:** Group comparison revealed an interaction of group and age that involved the temporal, parietal, and occipital lobes, bilaterally. Cortical thickness within the clusters showed a significantly greater decrease with age in the soccer players compared to the control group. There were no cluster with greater decline in cortical thickness in the control group. Within the soccer players, lifetime-estimate of headings correlated with cortical thickness in a cluster that in- volved the right hemisphere parietal and occipital lobes. -there was an overlap between the cluster with a significant correlation between life-time estimate of headings and the cluster with age x group interaction in the right inferolateral-parietal, temporal, and occipital cortex.The goalkeeper was among those with the highest cortical thickness. The two soccer players with hx mTBI injury were among those with the lowest cortical thickness.						

Secondary Neuroimaging Findings: Soccer players performed worse on the long delay recall condition. No significant correlations were found between cognitive or behavioral measures with lifetime-estimate of headings. TMT A positively correlated with cortical thickness in the right inferolateral-parietal cortex.						
Lead Author and Study Year	PMID	Modality	Sample size (M:F)	Age: mean (SD)	Sport	Level of Competition
Manning et al., 2020	32554762	fMRI & DTI	104 (0:104)	Contact: 73 (19.95 ± 1.5yrs) Non-contact: 31 (19.61 ± 1.87 yrs)	Rugby, Swimming, Rowing	University
Aim of Study: To longitudinally assess brain microstructure and function in female varsity athletes participating in contact and non-contact sports. **Concussion Criteria:** SCAT3; **Diagnosis:** Sports medicine physician; **Post- Concussion Symptoms**: NR **Accelerometry, neuropsychological or psychological data:** Head Impact accelerometer sensor bands **Neuroimaging Acquisition, Post-processing, & Analysis:** 3T MR Prisma, Siemens, 32-channel head coil. A coronal T2-weighted turbo spin echo sequence (echo time (TE)/repetition time (TR) = 85/7640 ms, flip angle = 120°, matrix size = 320 × 256, field of view (FOV) = 220 mm × 179 mm, number of slices = 43, slice thickness = 4 mm), a sagittal T1-weighted magnetization-prepared rapid acquisition gradient echo sequence (MPRAGE) (TE/TR = 2.94/2300 ms, flip angle = 9°, matrix size = 256 × 256, FOV = 256 mm × 240 mm, number of slices = 160, slice thickness = 1.2 mm) and a gradient-recalled multiecho 3D image (TE/TR = 10/52 ms, flip angle = 12°, matrix size = 448 × 448, FOV = 224 mm × 168 mm, Number of slices = 128, slice thickness = 1.0 mm) were acquired. 10-min rsfMRI gradient echo echo-planar imaging sequence (TE/TR = 30/2500 ms, flip angle = 90°, matrix size = 80 × 80, FOV = 240 mm × 240 mm, number of slices = 45, slice thickness = 3 mm) was performed. A spin echo DTI sequence (TE/TR = 79/7200 ms, matrix size = 98 × 98, FOV = 200 mm × 200 mm, number of slices = 64, slice thickness = 2 mm, b1 = 0, b2 = 1000 s/mm2, gradient directions = 64) was used. Diffusion data were analyzed with the Functional Magnetic Resonance Imaging of the Brain (FMRIB) Software rsfMRI data were preprocessed with the fMRI Expert Analysis Tool in FSL. Independent component analysis was used to identify resting-state networks including the DMN, lateral visual network, and cerebellar. -Imaging ROIs with significant differences among groups were explored further with a linear mixed- effects model within MATLAB to evaluate the main effect of participant group, time, and interaction. DTI and rsfMRI datawere acquired during the in-season and off-season if the athlete did not experience a diagnosed concussion within 6 months of entry into the study **Primary Neuroimaging Findings:** Concussion-free contact athletes during both the in- and off- season had greater connectivity between the DMN and the posterior cingulate cortex (PCC) compared to in- and off- season non-contact. Connectivity between the lateral visual network and areas throughout the occipital lobe was increased for in- and off-season contact athletes compared to in-season non-contact athletes. There were no significant differences in functional connectivity in the cerebellar RSN after correction for multiple comparisons. No significant differences in connectivity between the PCC and DMN in rugby athletes with and without a concussion history. Significant differences across all diffusion metrics between concussion-free contact athletes and non-contact athletes (corpus callosum, cingulum, and brainstem, portions of the superior longitudinal and inferior occipital fasciculi). Significant effect of group where AD was higher in the contact athletes and MD was						

higher in contact athletes compared to in-season non- contact athletes in the splenium and genu of the corpus callosum. MD, AD, and RD of the body of the corpus callosum had a significant group-by-time interaction, and main effects for group and time, and were all higher in both in- and off-season for contact compared to in-season non-contact. **Secondary Neuroimaging Findings:** FA in the brainstem was significantly associated with the SCAT immediate memory subtest scores.						
Lead Author and Study Year	PMID	Modality	Sample size (M:F)	Age: mean (SD)	Sport	Level of Competition
Mayinger et al., 2018	28092023	DTI	20 (20:0)	Collision: 15 (20.0 ± 1.0 yrs) Non-athlete: 5 (20.93 ± 1.1 yrs)	Football	University
Aim of Study: Tto evaluate longitudinal changes in the diffusion characteristics of brain white matter (WM) in collegiate athletes at three time points: prior to the start of the football season (T1), after one season of football (T2), followed by six months of no-contact rest (T3). **Concussion Criteria:** SCAT2; **Diagnosis:** Athletic trainer; **Post- Concussion Symptoms**: ImPACT **Accelerometry, neuropsychological or psychological data:** N/R **Neuroimaging Acquisition, Post-processing, & Analysis:** 3T Tim Trio system Siemens, 32-channel matrix head coil. DTI sequence parameters were TR/TE =10 s/89 ms, voxel size 2x2x2 mm, 60 diffusion directions with b = 1200 s/mm2 and 10 averages of b = 0. WM diffusion characteristics were analyzed using TBSS. Timepoint and individual specific diffusion values were obtained from the statistically significant voxel clusters. Average diffusivity values from significant voxels were plotted using GraphPad Prism. Statistically significant FA clusters were used to create an ROI. which was applied to the FA map to obtain FA values in that same ROI. Significant clusters of voxels identified in the athlete group were then applied to the control group, and diffusion values in these clusters were measured. All subjects underwent DTI at baseline/pre-season (T1), immediately post-season (T2), and six-months post-season (T3). **Primary Neuroimaging Findings:** Significant T1 to T2 increase in FA in the left parietal lobe. After six months of rest (T2 to T3) there was a decrease in FA in this same cluster. TBSS also identified a cluster of voxels with a significant T2 to T3 decrease in FA in a slightly different voxel cluster also located in the left parietal lobe. There were no significant changes in FA from T1 to T3 for either cluster. T1 to T2 increase in trace in the brainstem and in the left temporal lobe. After six months of rest (T2 to T3), there was a decrease in trace in this cluster. **Secondary Neuroimaging Findings:** Exposure among athletes ranged from 48 to 1850 total impacts (mean ± SD = 800 ± 515). There were no significant group mean declines in cognitive performance at any time point.						
Lead Author and Study Year	PMID	Modality	Sample size (M:F)	Age: mean (SD)	Sport	Level of Competition
Monroe et al., 2020	32861790	fMRI	24 (24:0)	Participants: 24 (20.2 ± 1.5 yrs) Contact: 13 Non-contact: 11	Soccer, Golf, Cross-country	University

Aim of Study: To examine the relationship between head-to-ball impact exposure and changes in functional connectivity in a core set of central autonomic regions and then to determine the relation between changes in brain and changes in behavior, specifically cognitive control. **Concussion Criteria:** NR; **Diagnosis:** Athletic trainer; **Post- Concussion Symptoms**: NR **Accelerometry, neuropsychological or psychological data:** Dot pattern expectancy task **Neuroimaging Acquisition, Post-processing, & Analysis:** 3T Philips Achieva, sensitivity encoding (SENSE) 32-channel head coil. T1-weighted fluid attenuated inversion recovery (FLAIR) sequence (flip angle = 90°; matrix size = 240 × 240; number of slices = 180; slice thickness = 2 mm). Functional images were acquired using a T2-weighted EPI sequence (TE = 29 ms; TR = 2000 ms; matrix size = 64 × 64; number of slices = 51; flip angle = 71°). FSLeyes was used to create ROIs. ROIs were placed in the ventral anterior insula, medial prefrontal and medial orbitofrontal cortices, amygdala and subgenual anterior cingulate cortex, periaqueductal grey, and hypothalamus. CONN functional connectivity toolbox was used to preprocess images and perform functional connectivity statistical analyses. Functional connectivity within the core central autonomic network for each participant at pre- and post-season was defined using partial correlations, which represent linear relationships between two nodes conditioned on all other connections in the network. GLM to determine whether head impact exposure (independent variable) was associated with changes in connectivity be- tween each pair of CAN nodes. A 'brain' matrix, representing thresholded and residualized post-season core CAN functional connectivity, and a 'behavior' matrix of residualized DPX scores, served as inputs to a partial least squares (PLS) correlation analysis. Athletes completed two rsfMRI scans, one before and one after the sea- son, within 2 weeks of the beginning and end of potential exposure to head-to-ball impacts **Primary Neuroimaging Findings:** Head-to-ball impact exposure was associated with changes in FC within a subset of 40 edges between all 14 nodes of the core CAN. The left insula, left hypothalamus, and left amygdala exhibited the greatest integration within this subnetwork, meaning they were most affected by head-to-ball impact exposure. The right amygdala and left and right medial PFC were least affected. PLS revealed CAN was associated with a decreased PBI (indicating a greater reliance on reactive cognitive control strategies), but not with a change in d-prime. **Secondary Neuroimaging Findings:** N/R						
Lead Author and Study Year	PMID	Modality	Sample size (M:F)	Age: mean (SD)	Sport	Level of Competition
Sollmann et al., 2018	29204342	DTI	25 (14:11)	Male: 14 (21.7 ± 1.3 yrs) Female: 11 (19.2 ± 1.8 yrs)	Hockey	University
Aim of Study: To identify and to characterize sex differences following exposure to repetitive subconcussive head impacts. **Concussion Criteria:** Per the Zürich consensus statement; **Diagnosis:** Specialist physician; **Post- Concussion Symptoms**: ImPACT **Accelerometry, neuropsychological or psychological data:** N/R **Neuroimaging Acquisition, Post-processing, & Analysis:** 3T MRI scanner, 8 channel head coil. A sequence with two averages and 60 non-colinear diffusion directions (TR/TE: 7015 ms/60 ms, b: 0 and 0.7 ms/mm2, 70 slices) was acquired using a 2.2 mm isotropic voxel size and a 100 × 100 matrix reconstructed into a 112 × 112 matrix with a resolution of 2 × 2 × 2.2 mm3. For analysis of WM diffusion properties, tract-						

based spatial statistics (TBSS) were carried out. The voxels that formed the skeletons were extracted for each individual scan. Pre-season data sets were subtracted from the post- season data sets, which generated skeletonized delta maps for each participant for FA, MD, AD, and RD, respectively. To identify voxel clusters with statistically significant group differences between females and males in the change in diffusion scalar measurements over the course of the play season, unpaired t-tests were performed applying the randomise command.
Primary Neuroimaging Findings: Differences between male and female participants in change over time. The statistically significant FA cluster primarily includes the superior longitudinal fasciculus (SLF), internal capsule (IC), and corona radiata (CR) of the right hemisphere. In the statistically significant cluster, FA values did not change significantly in male participants over the course of one season, whereas a decrease in FA in female participants was observed. The statistically significant MD cluster mainly includes the SLF, IC, CR, and the external capsule (EC) of the RH. In the significant voxel cluster, MD did not change significantly in male participants, whereas female participants demonstrated an increase in MD. Both AD and RD, values increased in female participants over the course of one season, whereas they did not in male participants.
Secondary Neuroimaging Findings: There were no statistically significant differences between female and male participants except for visual motor speed at post-season assessment, where male athletes demonstrated significantly improved function in visual motor speed compared to females.

Lead Author and Study Year	PMID	Modality	Sample size (M:F)	Age: mean (SD)	Sport	Level of Competition
Slobounov et al., 2017	28393012	fMRI & DTI & CBF	18 (18:0)	Participants: 18 (21.6 ± 1.28 yrs)	Football	University

Aim of Study: To examine the effects of repetitive collisions across a single competitive season in NCAA Football Bowl Subdivision athletes using advanced neuroimaging approaches.
Concussion Criteria: NR; **Diagnosis:** N/R; **Post- Concussion Symptoms**: NR
Accelerometry, neuropsychological or psychological data: BodiTrak system from HeadHealth Network -helmet sensors worn only at practices
Neuroimaging Acquisition, Post-processing, & Analysis: 3T Prisma MR Siemens, 32-channel head coil. T1-weighted 1-mm3 isotropic volumetric images (3 min 31 s), with cerebrospinal fluid (CSF) suppressed, were obtained to cover the whole brain with a 3D magnetization prepared rapid acquisition gradient recalled echo (3D MPRAGE) sequence with the following parameters: TE = 1.77 ms, time of inversion (TI) = 850 ms, TR = 1700 ms, flip angle = 9°, matrix size = 320 × 260 × 176, voxel size = 1 mm× 1 mm× 1 mm, receiver bandwidth = 300 Hz/pixel, and parallel acceleration factor = 2. 10-min echo-planar: 72 contiguous 2-mm axial slices in an interleaved order, time of echo (TE) = 35.8 ms, time of repetition (TR) = 2000 ms, flip angle = 90°, voxel resolution = 2 mm× 2 mm× 2 mm, matrix size = 104 × 104, 300 total volumes acquired. Regional cerebral blood flow data were acquired using 3D ASL (6 min 2 s): 40 axial slices, TE = 15.62 ms, TR = 4600 ms, voxel resolution = 1.5 mm× 1.5 mm× 3 mm, field of view = 192 mm× 192 mm, bolus duration = 700 ms, perfusion mode set at PICORE Q2TIPS, parallel acceleration factor = 2. White matter integrity was assessed using Tract-Based Spatial Statistics (TBSS) in FSL. Two-tail paired t-tests comparing Pre and Post measures of FA, MD, RD, and AD were applied. All cortical and subcortical volumes were extracted from the T1-weighted images via the FreeSurfer standard processing pipeline. Two-tail paired t-tests were applied to assess all regional cortical and

subcortical volume differences between Pre and Post measurements. AFNI software was used to generate the scripts to preprocess the rs-fMRI data. Correlation analyses of rs-fMRI time courses between the nodes of each network were performed. Comparison analyses between two sessions were performed on the transformed correlations with the seed regions. SWI data were examined for changes between Pre and Post measurements that might indicate development of leaks. Players completed both MRI scans: within one week before the athletic season began (before any contact practices began during pre-season and the regular season) and within one week after the last game of the season (post-season) **Primary Neuroimaging Findings:** No significant changes on the cortical and subcortical regional volumes were found. No significant changes were observed when contrasting Pre and Post average connectivity within each of the 17 networks. Similarly, no significant changes were observed when contrasting the Pre and Post within-network. Seed-based whole-brain functional connectivity analyses showed significant changes from Pre to Post in FC of clusters to seed regions were only observed for three of the four seed regions (right ICC, left ICC, left hippocampus). There was a statistically significant global increase of CBF in the cortex from Pre to Post. No significant changes were observed when contrasting DTI metrics (FA, MD, AD and RD) at Pre and Post measurements. **Secondary Neuroimaging Findings:** On a per-practice-session basis, each player received an average of 4.35 impacts meeting or exceeding 25G, with an average of 0.15 of these impacts meeting or exceeding 80G. No individual regions exhibited a statistically significant relationship between impact history metrics and measures either of CBF or functional connectivity. Greater increases in DMN connectivity over the course of the season, increase from Pre to Post in CBF, and statistically significant numbers of regions with decreased SWI signal intensity were found to be associated with athletes who experienced a broader/ higher distribution of per-practice-session impacts exceeding ≥80G.						
Lead Author and Study Year	PMID	Modality	Sample size (M:F)	Age: mean (SD)	Sport	Level of Competition
Talavage et al., 2014	20883154	Task based fMRI	11 (11:0)	Participants: 11 (Range: 15-19 yrs)	Football	Highschool
Aim of Study: To examine neurological performance and health in the presence of head collision events in high school football players. **Concussion Criteria:** Clinically observed impairment as diagnosed by team physician (COI+). Deviant ImPACT re- tests were said to be positive for a functionally observed impairment (FOI +); **Diagnosis:** Team physician; **Post- Concussion Symptoms**: N/R **Accelerometry, neuropsychological or psychological data:** Head Impact Telemetry **Neuroimaging Acquisition, Post-processing, & Analysis:** 3T General Electric Signa HDx,16-channel brain array. Whole-brain high-resolution images (3D-FSPGR; 1mm isotropic resolution) were acquired, including the cerebellum. Three functional runs were conducted of a visual working memory (N-back) paradigm, using gradient-echo echo planar imaging (TR/TE = 1500/26 msec; matrix = 64 · 64; FOV= 20 cm; 34 slices; 3.8mm thickness; 117 volumes). In each run subjects per- formed one block (15 presentations, 3-sec interval, 5 targets per block) each of 0-, 1-, and 2-back tasks for single letters. Subjects responded by dominant index finger via fiberoptic button box. The order of the task blocks in the three runs was counter-balanced within each session, and across assessments. Data were analyzed using AFNI. Pre-processing included slice timing correction, motion correction, normalization to Talairach space, and 8-mm gaussian smoothing for inter-subject comparison. Final analysis for each subject was affected on concatenated data, using a general linear model approach with Gamma Variate hemodynamic response function (without derivatives). The contrast of interest is a comparison between 2-back and 1-back working memory tasks, with statistically significant activation. Changes in fMRI activation were assessed using the 116 anatomically defined regions of interest (ROIs) from MarsBaR.						

Cross-modality analyses were performed to assess whether subsequently observed changes in fMRI assessment of physiology were correlated with head collision events. Alterations of hemodynamic response signal amplitudes observed during in-season fMRI relative to that observed within the same subject in the pre-season assessment, was compared to the number of head-collision events measured by the HIT System in the week prior to the in-season assessment. This assessment was performed both on an anatomical ROI basis, and on a more global basis, for an aggregated ROI encompassing nearly the entirety of the frontal lobe, excluding only the precentral gyrus. A 3x2 implementation of the test was used, in which the player categories are considered the treatments, and the observation is either a decrease or a non-decrease in the in-season frontal lobe hemodynamic response signal amplitude, relative to that obtained from the pre-season assessment, evaluated on a per- subject basis. Athletes completed ImPACT and fMRI assessments at pre-season, in-season (within 48h of a game or 72h of diagnosis of concussion), and post-season (1-3months following season). Players who were diagnosed by the team physician with a concussion were deemed to be positive for clinically observed impairment and are labeled COI+. Players who exhibited deviant ImPACT retests were said to be positive for a functionally observed impairment (FOI+). Scores within the 99% confidence intervals were negative. Collision events recorded by the HIT System for each player were analyzed using a one-way analysis of variance (ANOVA).
Primary Neuroimaging Findings: fMRI data for COI+ /FOI + players revealed alterations in the pattern and amplitude of signal differences observed when contrasting the 2-back and 1-back memory tasks, particularly in the posterior middle and superior temporal gyri. In-season fMRI data for COI - /FOI – players showed no differences in 115 of the 116 ROIs, both on a within-player basis, and relative to the group random effects analysis. (exception: right cerebellum 3, which exhibited decreased activation in three players). At post-season, COI- /FOI - players ImPACT scores and task performance were again found to be within test/re-test limits. COI-/FOI- at all in-season assessments, significantly decreased fMRI activation in the dorsolateral prefrontal cortex and cerebellum. In particular, when the 2-back and 1-back working memory conditions were contrasted, activation in the DLPFC changed from favoring the 2-back condition, to favoring the 1-back condition. When compared with COI+ /FOI + players, the COI- /FOI + players were found to be at least as impaired (as demonstrated by both ImPACT and fMRI measures) as the known-concussed group.
Secondary Neuroimaging Findings: Three players were categorized as COI+ /FOI +, four as COI- /FOI-, and four as COI- /FOI +. The total number of collision events experienced by the COI- /FOI + group was significantly greater than that of any other group and exhibited more high magnitude (> 80g) collision events directed to the top front of the helmet immediately above the DLPFC. The number of head collision events experienced in the week preceding an in-season assessment was correlated with changes in fMRI activation for the 2-back versus 1-back contrast of interest.

Table 2. Pre-season and demographic and clinical results for contact and collision athletes.

	Pre-season			Post-season	
	Contact (n = 7)	Collision (n = 12)	p(g)	Contact (n=7)	Collision (n-12)
Age (yr) *M(SD)*	19.71 (1.38)	19.50 (1.09)	0.71 (0.17)	-	-
Age at first sport *M(SD)*	7.28 (3.68)	4.58 (0.90)	0.11(1.12)	-	-
Concussion history *M(SD)*	1.57 (1.51)	0.58 (0.90)	0.09 (0.82)	1.29 (1.11)	0.58 (0.67)
PHQ-9 total score *M(SD)*	4.29 (2.93)	1.58 (1.78)	0.02 (1.15)	5.57 (4.79	2.82 (4.58)
GAD-7 total score *M(SD)*	4.29 (3.09)	1.08 (1.44)	0.03 (1.41)	4.14 (3.08)	2.00 (2.59)
SCAT total symptoms *M(SD)*	4.71 (3.4)	1.33 (3.11)	0.04 (1.00)	4.14 (4.60)	2.00 (3.22)
SAC subtotal *M(SD)*	27.43 (1.81)	26.83 (1.19)	0.40 (0.39)	26.86(0.90)	27.92 (1.56)
AUDIT-C total score *M(SD)*	3.15 (1.77)	3.11 (1.83)	0.97 (0.02)	3.29 (2.36)	3.17 (1.34)
Marijuana (non-users/users)	4:3	11:1	0.07 (0.84)*	5:2	11:1

Note: g = Hedge’s g; *chi square

Table 3. Pre-season and post-season ANT-I scores for contact and collision athletes

	Pre-season		Post-season	
	Contact (n = 7)	Collision (n = 12)	Contact (n = 7)	Collision (n = 12)
Alerting				
Tone M(SD)	617.11 (79.29)	580.21 (56.29)	596.92 (60.67)	543.35 (40.10)
No tone M(SD)	618.44 (128.88))	580.83 (116.93)	606.97 (59.36)	549.76 (42.03)
Orienting				
Valid cue M(SD)	573.47 (81.32)	539.84 (49.88)	559.18 (53.23)	508.12 (29.60)
Invalid cue M(SD)	635.39 (80.11)	597.07 (63.64)	613.70 (64.91)	559.09 (51.00)
No cue M(SD)	644.46 (77.57)	604.66 (60.75)	632.96 (64.85)	572.46 (50.03)
Executive Control				
Congruent M(SD)	575.34 (75.83)	540.10 (52.00)	561.36 (57.98)	512.25 (37.20)
Incongruent M(SD)	660.21 (81.10)	620.95 (61.41)	642.53 (62.35)	580.86 (44.76)

Table 4. ICA results

Network	Primary Regions	Cluster size	MNI coordinates x	y	z	T value	mass p-FDR
Main effect of time (Collision(.5)Contact(.5)Pre(-1)Post(1))							
DMN	Superior Parietal Lobule Right	645	18	-46	70	-6.85	0.001
	Supramarginal Gyrus, anterior division Left	357	-50	-26	32	-6.13	0.004
	Superior Frontal Gyrus Left	268	-22	-4	70	-7.61	0.006
	Supramarginal Gyrus, anterior division Right	145	56	-32	40	-6.41	0.043
	Superior Parietal Lobule Left	133	-16	-58	68	-5.82	0.043
	Frontal Pole Right	115	42	48	-16	6.27	0.043
Follow up: Contact (n=7)Pre(-1)Post(1)							
DMN	Lateral Occipital Cortex, superior division Right	401	8	-64	68	-19.32	0.001
	Supramarginal Gyrus, anterior division Left	316	-48	-28	42	-27.85	0.001
	Superior Frontal Gyrus Left	212	-22	-6	60	-13.75	0.003

	Lateral Occipital Cortex, superior division Right	188	28	-66	38	-10.18	0.003
	Lateral Occipital Cortex, superior division Left	152	-14	-78	58	-16.42	0.003
	Superior Parietal Lobule Left	110	-34	-38	38	-12.81	0.010
	Precentral Gyrus Right	51	26	-6	48	-10.08	0.045
	Superior Parietal Lobule Right	45	34	-40	50	-11.03	0.045
Main effect of group(Collision(1)Contact(-1)Pre(.5)Post.5))							
DAN	Superior Frontal Gyrus Right	264	-6	42	36	7.33	0.035
	Supramarginal Gyrus, anterior division Right	191	54	-30	48	-6.09	0.037
Follow up: Preseason Collision(1) Contact(-1)							
DAN	Superior Frontal Gyrus Right	285	-8	40	34	6.43	0.021
	Supramarginal Gyrus, anterior division Right	166	54	-30	48	-5.15	0.044

Note: DAN, dorsal attention network; DMN, default mode network.

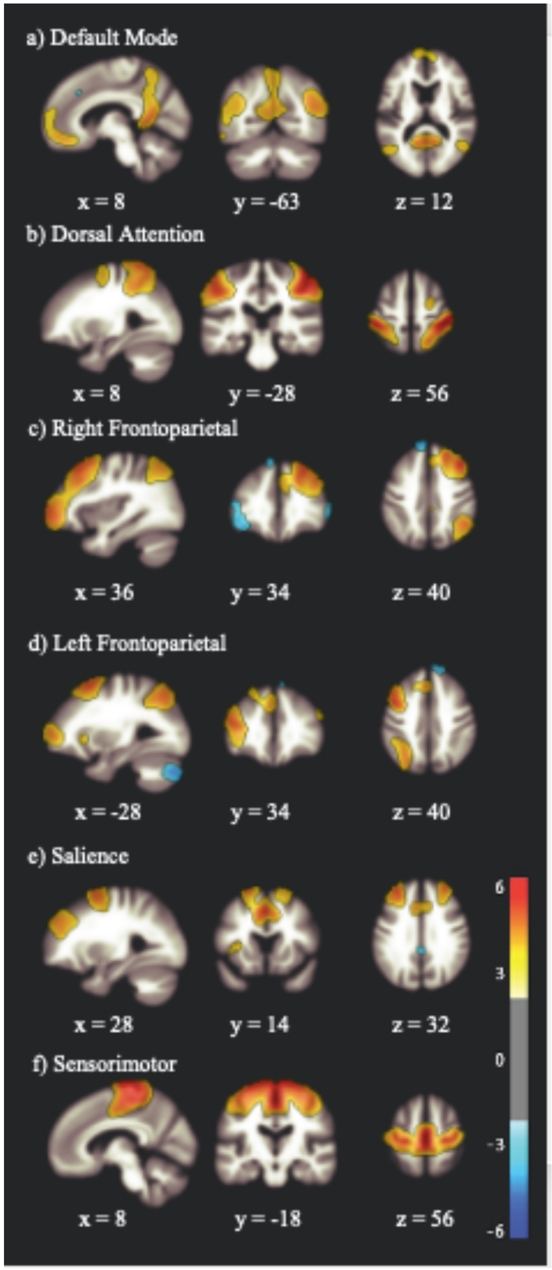


Figure 1. Results of ICA showing components with high match to template for the a) DMN, b) DAN, c) left FPN, d) right FPN, e) SN, and f) SMN.

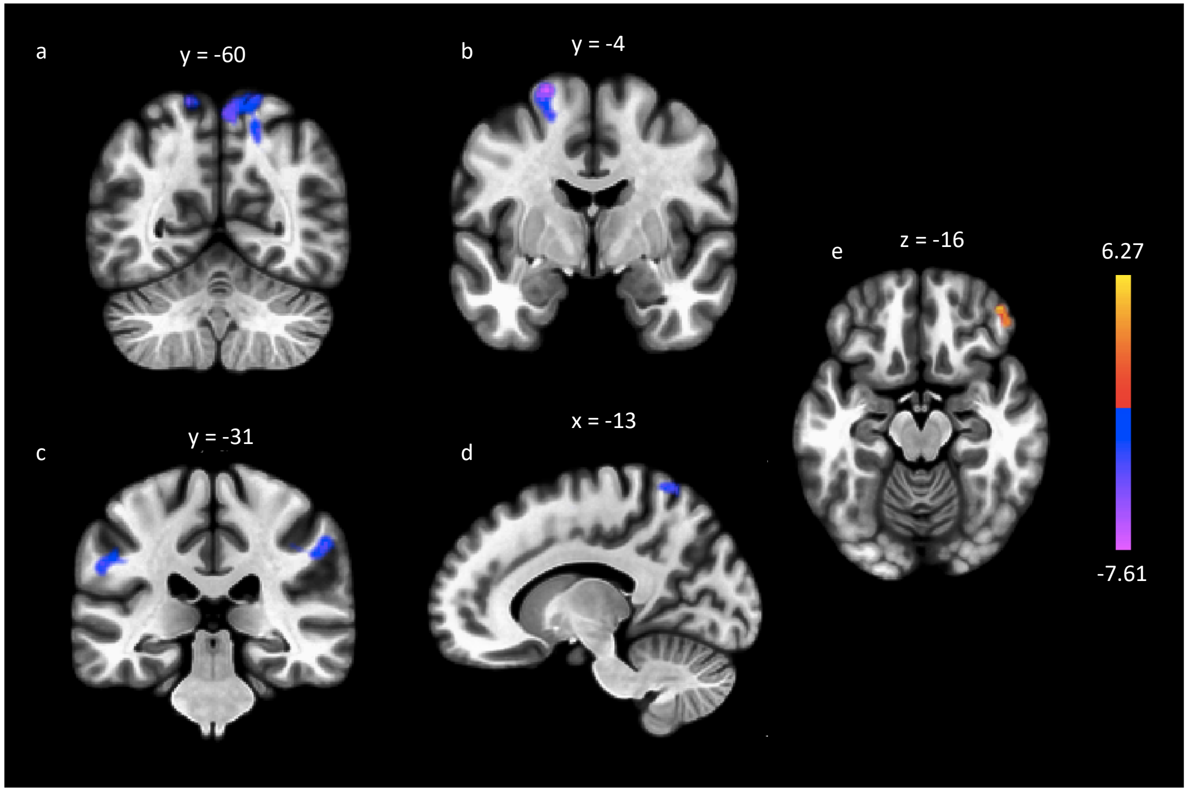


Figure 2. Independent component analysis (ICA) main effect of time in the default mode network (DMN), showing decreased connectivity with the a) right superior parietal lobule, b) left superior frontal gyrus, c) bilateral supramarginal gyrus, d) left superior parietal lobule, and e) increased connectivity with the right frontal pole at post-season compared to pre-season.

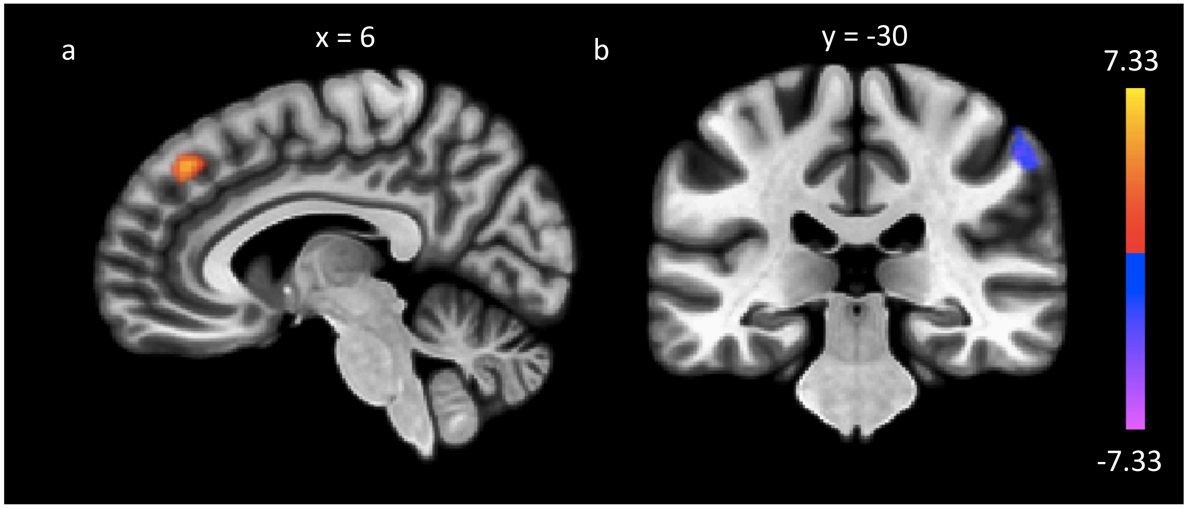
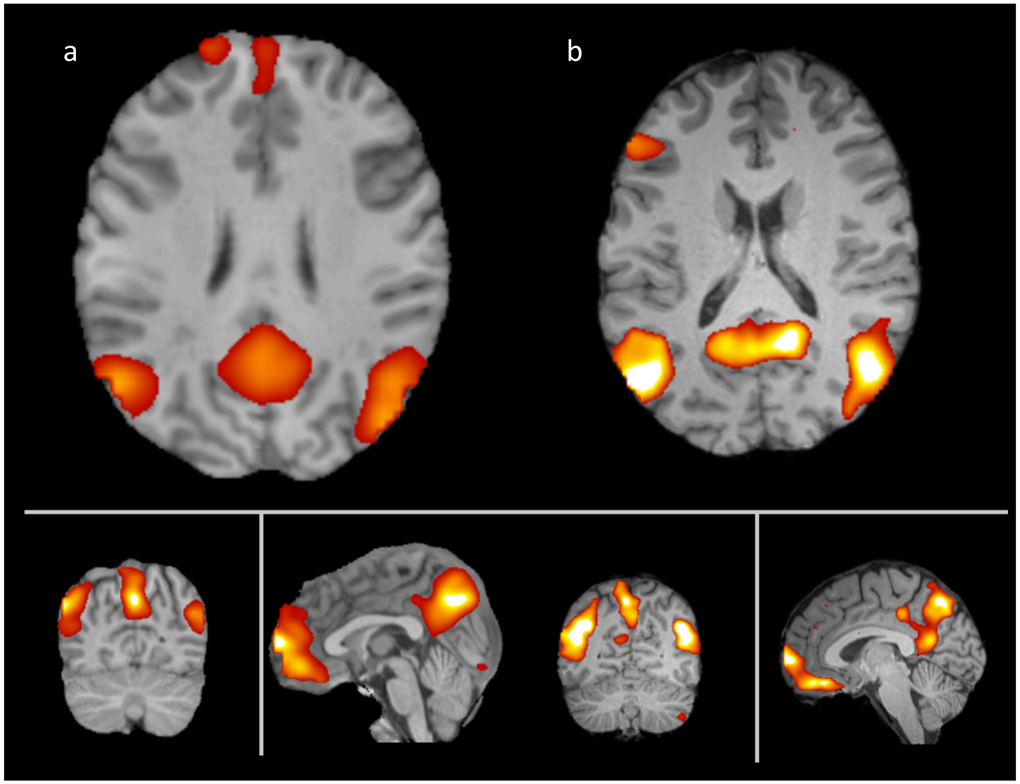


Figure 3. Independent component analysis (ICA) main effect of group in the dorsal attention network (DAN), showing a) increased connectivity with the right superior frontal gyrus and b) decreased connectivity with the right supramarginal gyrus in collision players compared to contact players.

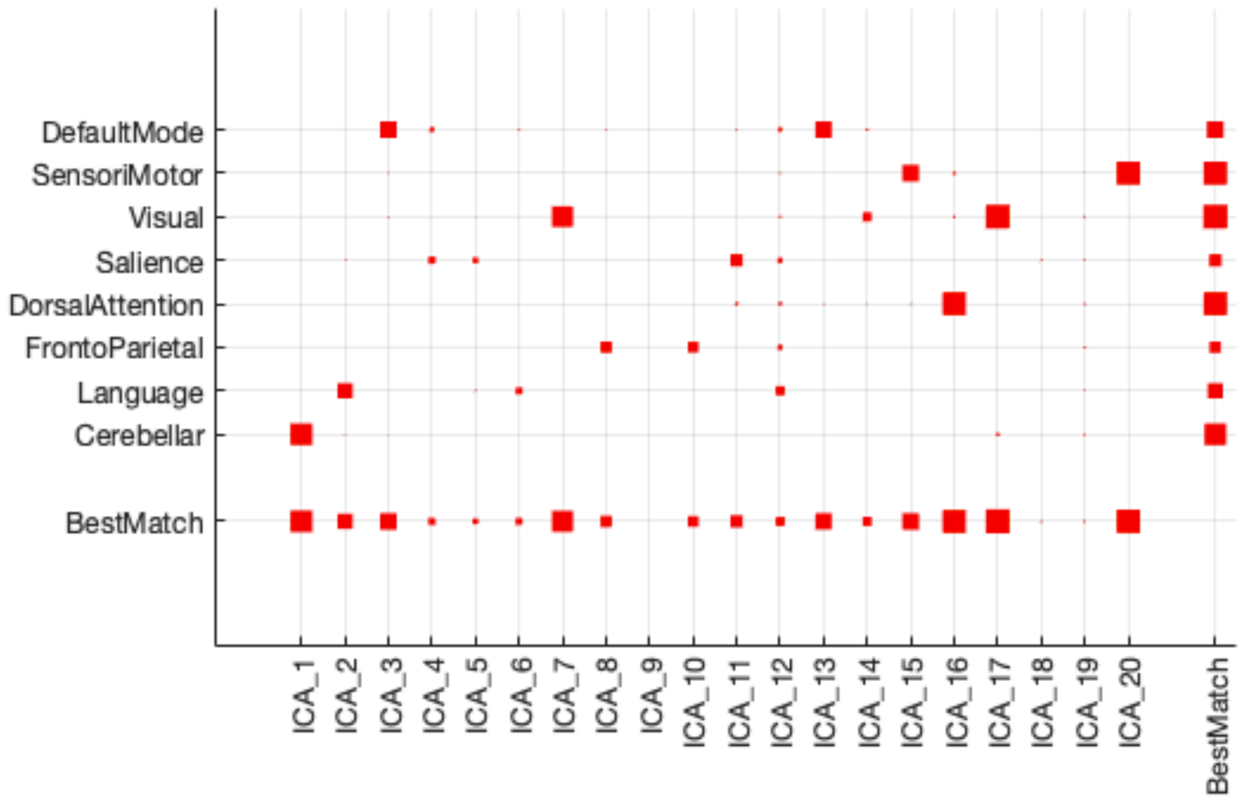
APPENDICES

Appendix A



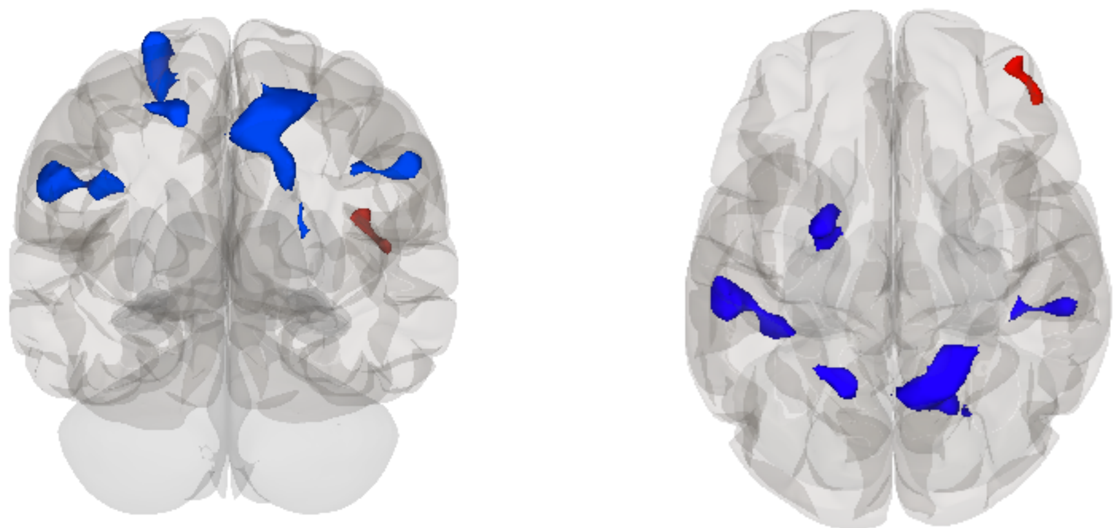
Example of the group level default mode network (DMN) component back projected at the individual subject level by independent component analysis (ICA), performed using a) AFNI and b) CONN toolbox.

Appendix B

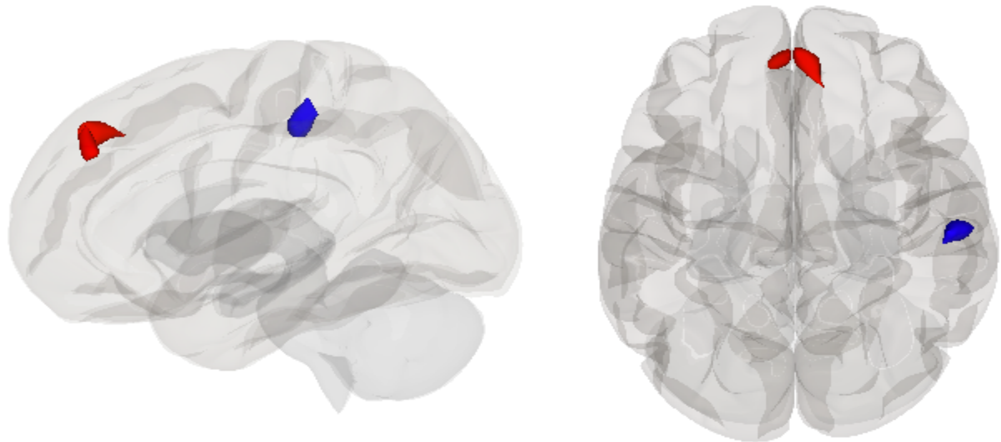


Spatial match-to-template showing correlation between ICA components and functional network templates supplied by the CONN toolbox, where correlation size is depicted by the size of the red square.

Appendix C



Glass brain rendering showing independent component analysis (ICA) main effect of time in the default mode network (DMN), showing decreased connectivity with the right lateral occipital cortex and superior parietal lobule, left superior frontal gyrus, bilateral supramarginal gyrus, left superior parietal lobule and lateral occipital cortex, and increased connectivity with the right frontal pole at post-season compared to pre-season.



Glass brain rendering showing independent component analysis (ICA) main effect of group in the dorsal attention network (DAN), showing increased connectivity with the right superior frontal gyrus and decreased connectivity with the right supramarginal gyrus in collision players compared to contact players.