European Journal of Sport Science

ISSN: 1746-1391 (Print) 1536-7290 (Online) Journal homepage: https://www.tandfonline.com/loi/tejs20

Sport experience is correlated with complex motor skill recovery in youth following concussion

Marc Dalecki, Diana J. Gorbet, Alison Macpherson & Lauren E. Sergio

European Journal of Sport Science, 2019
https://doi.org/10.1080/17461391.2019.1584249

Sport experience is correlated with complex motor skill recovery in youth following concussion

MARC DALECKI[1], DIANA J. GORBET[2,3], ALISON MACPHERSON[2], & LAUREN E. SERGIO[2,3]

[1]*School of Kinesiology, Louisiana State University, Baton Rouge, LA, USA;* [2]*School of Kinesiology and Health Science, York University, Toronto, ON, Canada &* [3]*Centre for Vision Research, York University, Toronto, ON, Canada*

ABSTRACT
A previous study showed prolonged cognitive–motor integration (CMI) deficits in youth with a history of concussion who were classified as asymptomatic by current return-to-play protocols, highlighting potential differences between clinical symptom recovery and skill recovery. The present study examines factors that may influence skilled performance recovery (defined as matching the skill level of no-concussion history peers) post-concussion in a similar cohort. Sixty-four asymptomatic youth ($M = 13$ yrs.) soccer, hockey, and lacrosse players with a concussion history ($M = 14$ months post-concussion) who returned to play and sixty-two age-matched team members with no previous concussion participated in this study. They performed two touchscreen-based eye–hand coordination tasks, including a direct interaction and a CMI task. We analysed the relationship between CMI performance and concussion history, and whether age, sex, number of concussions, and years of sport experience in their sport affected skill recovery. Individuals with concussion history and higher amounts of sport experience (7–12 years) reached a performance level matching their no-history peers quicker (after 12 months) than those with concussion history and lower sport experience (1–6 years; recovery after 30 months). This effect was independent of the number of concussions, age, and sex. The present results point towards an important role of eye–limb coordination-related sport experience in functional CMI recovery post-concussion. Youth with a concussion history but greater sport experience may have more skill-related motor "reserve". This reserve may directly aid in behavioural recovery post-concussion, or the greater neurological efficiency associated with athletic experience provides a compensatory mechanism that provides faster functional recovery.

Keywords: *Mild traumatic brain injury, children, adolescents, return to play, cognitive–motor integration*

Highlights

- Our study indicates an important role of sport-related visuomotor experience for complex motor skill recovery in youth with a history of concussion.
- Youth with a concussion history and higher levels of eye–limb coordination-related sport experience had quicker motor skill recovery times (around 12 months) compared to their peers with less sport experience (around 30 months).
- These findings may underline a difference between assessments of readiness to return to play using current clinical assessment techniques and true time of sport-relevant skill recovery post-concussion.

Introduction

Concerns about short- and long-term effects of sport-related concussions and repeated head impacts suffered by athletes have become more prevalent in recent years (Mainwaring, Pennock, Mylabathula, & Alavie, 2018; Sollmann et al., 2018). Studies have shown links to mild cognitive impairment (MCI), Alzheimer's disease (AD) (Guskiewicz et al., 2005), memory loss, headache, and migraine 10–20 years post-concussion (Meehan 3rd & Bachur, 2009), as well as structural and functional brain changes in contact-sport players (Davenport et al., 2014; McAllister et al., 2001; Slobounov, Sebastianelli, & Simon, 2002; Solomon et al., 2016; Tremblay et al., 2013; Tremblay et al., 2014; Zhang et al., 2010). Another alarming feature of sport-related concussions is that there is a higher risk of getting another once you have had one,

Correspondence: Marc Dalecki School of Kinesiology, Louisiana State University, 71 Huey P. Long Field House, 70803, Baton Rouge, LA, USA. Email: mdalecki@lsu.edu

especially for young players within the first 6–12 months after they return to play post-concussion (Guskiewicz et al., 2003; Karlin, 2011). It is important to understand the mechanism(s) that underlie this increased vulnerability and to understand the factors that might be relevant for a safer return to play. There is an apparent gap between the time points of clinical recovery (usually 2–4 weeks) using current assessment techniques (e.g. SCAT 5, ImPACT, see McCrory et al., 2017), and underlying physiological recovery. An increasing number of studies suggest that multiple skill-related behaviours and underlying brain function and structure can take from 3 months to 3 years to return to pre-concussion levels (Dalecki, Albines, Macpherson, & Sergio, 2016; Slobounov et al., 2002; Slobounov, Gay, Johnson, & Zhang, 2012).

Our previous work has demonstrated a similar pattern of findings in children and adolescents with a history of sport-related concussion. Cognitive–motor integration (CMI) performance was impaired for up to 2 years post-concussion, despite all study participants being classified as asymptomatic by current return-to-play protocols (Dalecki et al., 2016). CMI requires the brain to concurrently implement elements of cognition and motor function to perform complex motor actions. This is an important skill in everyday life and in many sports, e.g. when passing a hockey puck and attending to the teammate on the left while skating to the right. CMI deficits post-concussion could be related to the increased risk for re-injury in players with a history of concussion. Specifically, although simple motor functions have likely recovered at return to play, motor functions requiring cognitive integration may not have fully recovered. It is, therefore important to gain knowledge about factors that may influence recovery of CMI capacities post-concussion, given its use during play.

Previous studies showed that post-concussive CMI deficits had an inverse relationship with age and skill level (Brown, Dalecki, Hughes, Macpherson, & Sergio, 2015; Dalecki et al., 2016; Hurtubise, 2016; Sergio et al., 2017). Thus, one might expect that more years of eye–limb coordination-related sports experience could compensate for CMI skill impairment. Age is another potentially relevant recovery factor since complex cognitive–spatial abilities (which are crucially relevant for cognitive–motor integration) emerge later in development than simple goal-directed reaching abilities (Lubans, Morgan, Cliff, Barnett, & Okely, 2010; Paus, 2005), possibly leading to faster CMI performance recovery in adolescents than in younger children. There are also sex-related differences in eye–hand coordination development and performance (Albines, Granek, Gorbet, & Sergio, 2016; Gorbet & Sergio, 2007), which may lead to different CMI recovery times between girls and boys. Therefore, in the present study, we examine factors that may influence the recovery of CMI performance in youth with a history of concussion, such as age, sex, number of concussions, and years of sport experience in eye–limb coordination sports.

Methods

Participants

Sixty-four youth with a history of sport-related concussion (13.14 ± 1.68 yrs.; 30 females; last concussion $M = 14.31 \pm 11.30$ months prior to testing, range: 0.25–48 months) and 62 healthy age-matched controls with no history of concussion (11.97 ± 1.87 yrs.; 29 females) participated in this study. Demographic data are summarised in the Supplementary file I, Tab. 1. Participants, parents, team-managers, and coaches were interviewed in order to obtain detailed information about the concussion history, i.e. the numbers and dates (month/year). The concussion history assessment was based on self-reports; however, participants were only included in the study if they reported that concussions were medically diagnosed and sport-related. At the time of testing, all participants were reported to be healthy, not diagnosed with a current concussion, and were fully participating in their team sport. All concussion history participants were defined as "asymptomatic" in accordance with current return-to-play protocol guidelines at the time of testing, i.e. SCAT 3 and Child SCAT 3 (Kissick & Johnston, 2005; McCrory et al., 2013). Note that concussion history and control participants were recruited from the same hockey, soccer, and lacrosse teams. In addition to demographic data (age, sex) and type of sport, we recorded information about when participants started playing their sport (year). This allowed us to calculate the years of eye–limb coordination-related sport experience ("years of sport experience"). Fifty-six participants in the concussion history group and 54 participants in the no-history group played on select level, and 8 players from both groups played on recreational level (cf. dataset in supplementary file IV). Due to study restrictions, we were not able to access direct clinical information about concussion severity or the time of return to play. Testing took place in the greater Toronto area, Ontario, Canada, between 2013 and 2015. The study protocol was approved by York University's Ethics Review Board and conformed to the standards of the Canadian Tri-Council Research Ethics guidelines. Parents, coaches, and children/

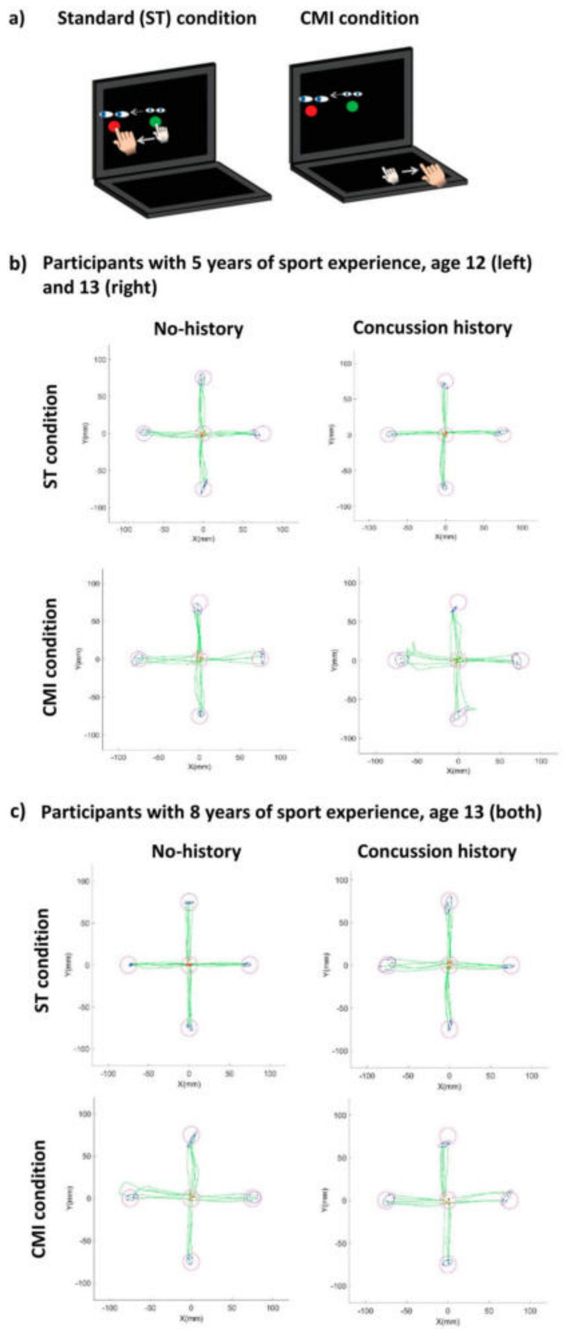

Figure 1. Schematic description of the experimental tasks. In a standard task with direct goal interaction (condition ST, (a) left image), participants slid their finger on a touch screen to move a cursor from a central target to one of four peripheral targets. In the cognitive–motor integration task (condition CMI, (a) right image), targets were in a different plane from hand motion, and feedback was reversed 180° (i.e. there was a decoupling between viewed target location and hand motion). In each trial, a peripheral target was presented either at the top, right, bottom, or left of a central target. Figure (b) and (c) show typical full hand path data of four participants, aged 12 and 13 years, performing the ST and CMI condition: Two participants with no history of concussion, and two with concussion history, with (b) five years of sport experience, and (c) eight years of sport experience. Note the poorer hand path of the participant with a concussion history and five years of sport experience when compared to the other participants in the CMI condition.

adolescents signed written informed consent/assent forms before participating in this study. Note that 50 of the concussion history and 49 of the no-history control group were also included in a previous study (Dalecki et al., 2016).

Procedures

Participants performed two visuomotor transformation tasks that required sliding the index finger of the dominant hand along an Acer Iconia 6120 dual-touch screen laptop, which has touch screens in the vertical and horizontal planes. Participants slid their finger from a central home target to peripheral targets in two different conditions. The “Standard” condition (ST) was the standard visuomotor mapping task, where the spatial location of the viewed target and the required movement were in alignment (i.e. hand movements were made on the vertical screen directly to visual targets) (cf. Figure 1(a), left image). The “Cognitive–motor integration” condition (CMI) was a non-standard visuomotor mapping task. This task included two levels of decoupling between vision and action: targets were again viewed on the vertical touch screen, but participants had to slide their finger along the horizontal touch screen, and in the opposite direction of a presented target (feedback reversal). That is, to move the cursor to the left, they had to slide their finger to the right, etc. (cf. Figure 1(a), right image).

The peripheral targets presented on the vertical touch screen were of 20 mm diameter, red coloured and presented to the left, right, above or below the central target (also 20 mm in diameter). The distance between the centres of the peripheral and central target (i.e. the screen centre) was 75 mm. The task itself was displayed on a 170 × 170 mm black square with the surrounding background coloured grey, in order to maintain a constant visual border. There were a total of 20 trials (i.e. 5 to each peripheral target) per condition, thus, altogether 40 test trials per participant. Trials were presented in a pseudo-randomised order to the peripheral targets in both conditions.

The trial timing and required responses of participants were as follows for the ST condition: (1) a green coloured centre target was presented on the vertical touch screen. (2) Participants touched the target with the index finger of their dominant hand. The target then changed colour to yellow. (3) After holding the centre target for 4000 ms a red peripheral target appeared and the centre target disappeared, serving as the “go-signal” for participants to concurrently look at the target and slide their index finger along the touch screen to move the cursor to the target. (4) Once the peripheral target was reached and held for 500 ms, the peripheral target disappeared and the trial ended. (5) The next trial began with the presentation of the centre target after an inter-trial interval of 2000 ms. The sequence was the same for the CMI condition, but participants moved their finger along the horizontal touchscreen in the opposite direction of the presented target to move the cursor on the vertical screen.

The order of performing the ST and CMI conditions was randomised across participants in each group. To ensure task comprehension, each participant performed two practice trials in each direction in both conditions. Participants were instructed to move as quickly and accurately as possible, and ambient distractions were kept to a minimum. Participants had full vision of their hand and fingers. The experimenter monitored participant's eye movements during the experiment and if incorrect movements were made, participants were reminded to always look towards the target and not to their hand. Those incorrect movements were less than 2% of trials and were eliminated before final data analysis. Data processing details are presented in the Supplementary File II.

Dependent measures

The dependent variables of interest from the visuomotor transformation tasks were reaction time (RT), ballistic movement time (MT), total movement time (TMT), ballistic path length (BallPL), path length (PL), peak velocity (PeakVel), as well as movement accuracy and precision variables (AE, VE).

Performance timing. Mean reaction time (RT) across trials was calculated as the time between disappearance of the central target and movement onset, i.e. the participant began the movement execution by sliding the cursor towards the target. Movement time (MT) was calculated as the time between movement onset and the first movement offset, thereby representing the ballistic initial movement without corrective movements. Total movement time (TMT) was calculated between movement onset and final movement endpoint (i.e. reaching the peripheral target). The peak velocity (PeakVel) was the maximum velocity in mm/s during the ballistic movement.

Pathlength. Measurements of pathlength were recorded for each trial. The ballistic pathlength (BallPL) was quantified as the distance in mm between the starting position and the endpoint of the first ballistic movement (i.e. distance covered during the ballistic movement time). Full pathlength (FullPL) was calculated as the distance between start and end location of the entire movement (i.e. including corrections). Movements comprising curves or deviations from a straight path between the central and peripheral target would thus result in a longer pathlength.

Endpoint analysis. The constant absolute error (AE), i.e. the endpoint accuracy, was determined as the distance between the average movement endpoint for each target location ($\sum x/n$, $\sum y/n$) and the actual target position (defined by the x and y coordinates at the centre of the target). Variable error (VE), i.e. the endpoint precision, was determined as the distance between the endpoints of the individual movements ($\sigma 2$) from their mean movements.

Direction reversals. Direction reversals (DR) were only applicable in the CMI condition. They were calculated when there was a deviation of more than ± 90° from the straight line between the centre and peripheral target in either direction during the first half of each movement, and were recorded as a percentage of completed trials.

Statistical analysis

Trials containing outcome measures >2 standard deviations (SDs) away from the mean for a given condition in a given participant were considered outliers and removed before statistical analysis. All remaining data were checked for normal distribution (Shapiro–Wilk's test) and sphericity (Mauchly's test), and were Greenhouse-Geisser corrected where necessary. Statistical analyses were performed using SPSS statistical software (IBM Inc.). Statistical significance levels were set to $\alpha < 0.05$.

Visuomotor task performance variables. For all dependent measures (RT, MT, TMT, PeakVel, BallPL, FullPL, AE, VE), effects of group (Concussion history, No-history) and condition (ST, CMI) were analysed using a repeated-measures mixed ANOVA. When there were significant main or interaction effects, pair-wise comparisons were used. We additionally performed ANCOVA's with the covariates sex, age, and number of concussions. Also, a separate analysis using sex and age as main effects was run to test for any sex-related or age-related behavioural differences. The number of direction reversals (DRs) in the CMI condition was compared between groups using a one-way ANOVA.

Relationship between CMI task performance and concussion history. To investigate whether possible CMI performance deficits were related to the time since the last concussion, we correlated the dependent main variables of the CMI condition with the time since last concussion (in months) with a linear regression analysis. The precise time since the last concussion was not available for nine participants (marked as "N/A" in the Supplementary file I, Tab. 1). These individuals were excluded from the correlation analysis. The estimates of timing for these participants fit within the time range of the other participants. Therefore, they were included in the main analysis (cf. above).

Recovery factors analysis. To investigate whether possible performance deficits in the concussion history group were related to age (years), sex, number of concussions, and sport experience (years), we performed correlation analyses between these factors and all CMI performance variables across all participants. We also performed the same analysis for the concussion history and control groups separately. Note that we had 13 participants in the concussion history and fourteen participants in the control group without precise "years of sport experience" data. These individuals were excluded from the correlation analysis and marked as "N/A" in the Supplementary file I, Tab. 1.

Results

The analysis using sex and age as main effects yielded no significant differences for all dependent variables. Thus, we merged data across sex and age. Notably, there was an effect of both concussion history and years of sport experience on rule-based skilled performance recovery. Figure 1(b) and (c) show typical hand path data from four participants performing the ST and CMI conditions. Note the poorer hand path of the participant with concussion history and five years of sport experience in the CMI condition (Figure 1(b), bottom right image) when compared to the other participants.

CMI performance and relationship to concussion history

Participants with a history of concussion showed significant CMI deficits and a significant relationship between the time since last concussion and CMI performance. ANOVA outcomes and descriptive statistics are summarised in the Supplementary file III, Tab. 2. Pair-wise comparisons revealed significant differences in the CMI condition between groups (Concussion history, No-history) for MT, TMT, PL, BallPL, and AE. Figure 2(a) summarises the mean results for total movement time (TMT), showing that the performance deficit in the concussion history group was most pronounced in the CMI condition. Similar patterns were observed for MT, PL, and BallPL.

The correlation analysis between CMI measures and the time since concussion yielded significant effects for MT ($r = -0.314$, $p < 0.05$), TMT ($r = -0.334$, $p < 0.05$), and PeakVel ($r = 0.373$, $p < 0.01$). All other CMI and ST measures showed no significant relationship to time since last concussion (all $p > 0.05$). Figure 2(b) shows the fitted regression line between total movement time in the CMI condition and the time since the last concussion. Also shown is the mean total movement time in the CMI condition of the participants with no-history of concussion (along the x-axis, grey solid line; the grey dashed lines represent the confidence interval) to illustrate the baseline performance of the age-matched controls. Notably, the regression line for participants with a concussion history does not cross the baseline of the no-history controls until approximately 18 months (the confidence interval ranges from 10 to 24 months). Similar patterns were observed for MT and PeakVel.

Recovery factors analysis

Age, sex, and number of concussions showed no significant effects on CMI performance recovery post-concussion (all $p > 0.05$). However, there was a significant relationship between years of sport experience and CMI performance across all participants for MT ($r = -0.214$, $p < 0.05$), TMT ($r = -0.226$, $p < 0.05$), VE ($r = -0.198$, $p < 0.05$), and DR ($r = -0.273$, $p < 0.01$). When examining the two groups (Concussion history, No-history) separately, we found a significant relationship between years of sport experience and CMI performance in the concussion history group for MT ($r = -0.305$, $p < 0.05$), TMT ($r = -0.275$, $p < 0.05$), PL ($r = -0.288$, $p < 0.05$), BallPL ($r = -0.408$, $p < 0.01$), and DR ($r = -0.348$, $p < 0.01$), but no significant relationships in the no-history control group (all $p > 0.05$). Accordingly, Figure 2(c) shows the regression line for the CMI performance variable total movement time (TMT) of concussion history participants and the non-significant trend line of no-history controls. The regression lines of the concussion history and no-history group are distinctly separated when participants have had less sport experience (approximately 1–6 years), but this difference disappears

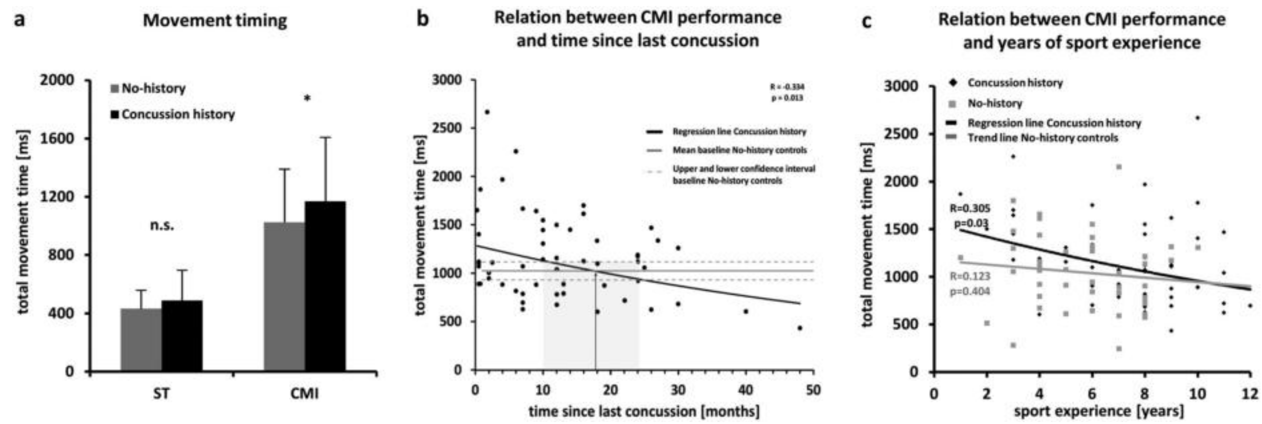

Figure 2. Mean (a) total movement time TMT across concussion history and no-history control participants in the ST and CMI conditions. * = $p < 0.05$, ** = $p < 0.01$, n.s. = non-significant. Error bars represent the standard deviation of the mean. (b) Relationship between the total movement time in the CMI condition and time since the last concussion for each child with concussion history (dots), represented by the regression line (black line). Also included is the mean total movement time of the CMI condition of the healthy controls with no concussion history (grey horizontal line). The grey dotted lines indicate the upper and lower confidence intervals of the control group's total movement time. The red arrow denotes where the two lines of the concussion history and no-history controls cross, and the grey shading shows the cross between the confidence interval for the control group and the regression line of the concussion history group. (c) Shows the relationship between the total movement time in the CMI condition and the years of sport experience, subdivided into the concussion history (black regression line) and no-history groups (grey trend line). Note the difference between the concussion history and no-history group lines with less (around 1–6 years) but not with a larger amount (around 7–12 years) of sport experience.

with increasing sport experience (approximately over 7 years).

We therefore separated the dataset into participants with 7–12 years and 1–6 years of sport experience in the concussion history and the no-history control group. The concussion history group allowed another regression analysis between CMI performance and time since last concussion (cf. Figure 2(b)) and participants with 7–12 years and 1–6 years of sport experience. There was a significant relationship between CMI performance and the time since last concussion for total movement time in the 7–12 years ($r = -0.392$, $p < 0.05$) and 1–6 years ($r = -0.604$, $p < 0.05$) of sport experience groups. Figure 3(a) shows this relationship for the 7–12 years (light grey solid line) and 1–6 years (black solid line) groups. The regression line of the concussion history participants in the 7–12 years of sport

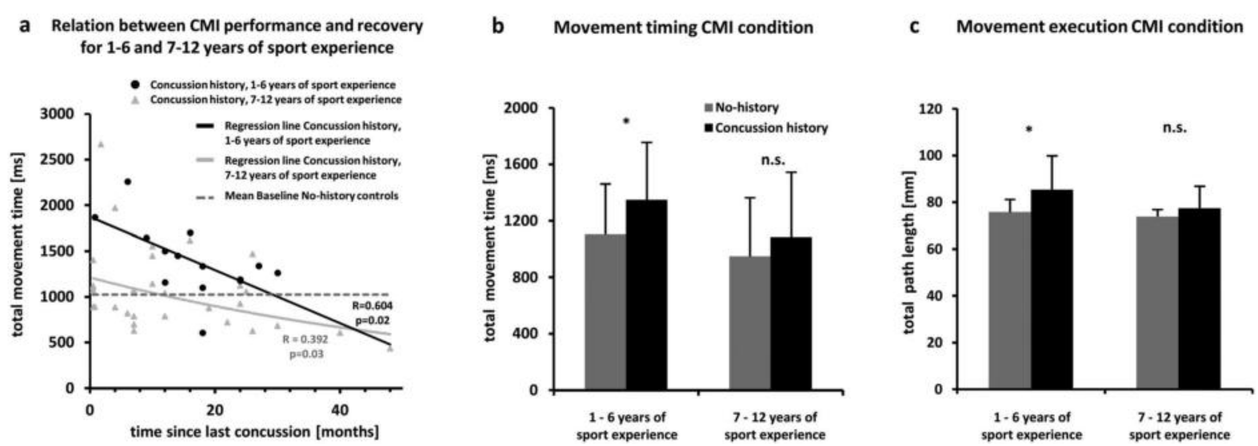

Figure 3. (a) Relationship between the total movement time in the CMI condition and the time since last concussion (months), subdivided into the 7–12 and 1–6 years of sport experience groups. Note the difference between the regression lines for both groups, and their different time points of crossing the mean baseline of the control group with no history of concussion (grey dashed line), which is around 12 months for the 7–12 years of sport experience group and around 30 months for the 1–6 years group. (b) Total movement time, and (c) full path length in the CMI condition across concussion history and no-history control participants subdivided into the 7–12 and 1–6 years of sport experience groups. Notably, concussion history participants with fewer years of sport experience had CMI performance deficits when compared to their peers with concussion history, but there was no significant difference between the two groups (7–12 years, 1–6 years) in the no-history control group. * = $p < 0.05$, ** = $p < 0.01$, n.s. = non-significant. Error bars represent the standard deviation of the mean.

experience group crosses the baseline of the no-history controls (dark grey dashed line) after about 12 months, but the 1–6 years of sport experience group crosses after about 30 months.

Finally, we performed one-way ANOVA and ANCOVA analyses for all CMI performance variables for both sport experience groups (1–6 years, 7–12 years) with the factor group (Concussion history, No-history). CMI performance variables showed significant differences between the concussion history and the no-history group in the 1–6 years of sport experience group (TMT, PL, and DR, all $p < 0.05$). ANCOVA revealed that this effect was independent of age, sex, and number of concussions (all $p > 0.05$). In contrast, there were no significant differences between the concussion history and the no-history control group in the 7–12 years of sport experience group (all $p > 0.05$). Accordingly, Figure 3 shows the results for (b) total movement time, and (c) full path length. Youth with concussion history and 1–6 years of sport experience had CMI deficits when compared to their no-history peers, an effect that was not present in the 7–12 years of sport experience group (see Figure 3 (b,c), and Supplementary file II). A similar pattern was observed for DR.

Discussion

The present study investigated the nature of cognitive–motor integration (CMI) skill recovery in youth with a history of concussion and potential factors that influence it. First, we replicated the previously reported prolonged CMI deficits in youth with a history of concussion (Dalecki et al., 2016). In the present study, these deficits lasted approximately 18 months post-concussion, which is in agreement with our previous study. Importantly, we found that youth with a concussion history and more eye–limb coordination-related sport experience demonstrated quicker CMI recovery compared to their peers with less experience. Specifically, youth with a concussion history and more years of eye–limb coordination-related sport experience reached CMI performance levels matching their non-concussed peers more quickly (after around 12 months) than those with a concussion history and less sport experience (after around 30 months, see Figure 3(a). Given that CMI performance is particularly important in contact sports, this finding of faster CMI skill recovery in individuals with greater sport experience is likely relevant for safe return to the field. Indeed, previous studies reported an up to threefold higher risk for young individuals with a history of concussion to receive another concussion or injury within 12 months of returning to game-play (Guskiewicz et al., 2003; Karlin, 2011).

Our findings suggest that the period of time in which individuals are at risk of re-injury after return to play could be shorter in individuals with more sport experience compared with individuals with less experience. In turn, this may leave the athlete with less sport experience more vulnerable to injury for a longer time, due to lingering CMI deficits. This idea is in line with findings of previous concussion history studies of youths, varsity athletes, and elite athletes. There was an inverse relationship between CMI deficits and skill level across these studies (Brown et al., 2015; Dalecki et al., 2016; Hurtubise, 2016; Sergio et al., 2017). All of these results strongly suggest an important role of visuomotor sport-related experience in compensation for CMI deficits post-concussion. This compensation is likely achieved due to the development of more efficient neurological processes for CMI (i.e. “motor reserve”). This motor reserve may also lower the risk of re-injury in young players after returning to play.

Although our data demonstrate that CMI deficits resolve more quickly with high levels of previous experience playing sports, these data do not allow us to determine whether this symptom resolution occurs due to underlying physiological recovery or compensation by motor reserve. Others have shown that individuals with a history of concussion that were cleared for game play performed similarly to those with no history of concussion during a visuospatial search task but with increased activation in fronto-parietal and cerebellar regions, which was explained as a potential compensatory mechanism (Slobounov et al., 2010). This decreased efficiency of visuomotor-related brain networks could potentially affect brain function in later life, as suggested by imaging data from retired professional full-contact sport athletes with concussion history (Tremblay et al., 2014). Therefore, while the faster recovery of CMI in individuals with high levels of sport experience could potentially decrease the risk of re-injury, this faster symptom resolution could come at the cost of the brain having to work harder to keep up performance, and possibly deficits later in life.

Prolonged CMI deficits with a concussion history may be due to disruptions in communication between brain regions responsible for planning and execution of cognitive–motor integration (Gorbet & Sergio, 2009; Gorbet & Sergio, 2016; Granek & Sergio, 2015; Hawkins, Sayegh, Yan, Crawford, & Sergio, 2013; Sayegh et al., 2014). Studies have indeed reported fronto-parietal network changes post-concussion (Slobounov et al., 2010; Tremblay et al., 2014). The relationship between the rate of

CMI recovery and previous experience playing sports found here further supports this idea. Accordingly, several studies reported more efficient fronto-parietal networks with high levels of eye–limb coordination-related sport experience, e.g. in gymnasts, badminton, and basketball players (Di et al., 2012; Park et al., 2009; Wang et al., 2016).

In our present study, we did not find a relationship between age and the course of CMI recovery post-concussion. This result was unexpected since developmental changes are well known over childhood and adolescence (Lubans et al., 2010; Paus, 2005). Potential age-related effects may have been washed out because of the large sports-related experience range (1–12 years) in a group with a relatively smaller age range (8–15 years). A few other studies have reported sex-related differences in children and adults for bimanual and complex eye–hand coordination tasks, as well as in concussion rates and symptom-related recovery post-concussion (Albines et al., 2016; Black, Cat, Sergio, & Macpherson, 2016; Gorbet & Sergio, 2007; Karlin, 2011; Lenroot & Giedd, 2010). However, we did not find effects of sex on CMI recovery or performance. This lack of sex-related differences may be related to the fact that based on their ages, most of our participants were likely pre-pubescent, and therefore potential sex differences due to hormonal influences, neck muscle development, and body mass may not yet have been very prominent in this group (Chiang Colvin et al., 2009; Collins et al., 2014; Covassin, Schatz, & Swanik, 2007; Tierney et al., 2005).

Limitations

Although our sample size was relatively high overall, a larger sample size would be helpful for investigating the interplay between a history of sport-related concussion and potential recovery-related factors such as age, sex, and years of sport experience. Another limitation of the present study was that the assessment of concussion history was based on self-reports. Therefore, although interviews included participants, parents, coaches, and team managers, potential errors are possible due to imprecise memory. However, potential participants were excluded from the study when reports of concussion history or years of sport experience data were incomplete, vague, or inconsistent across people who were interviewed. Nevertheless, the lack of direct confirmation of concussion history, severity, and the exact timing of return to play from clinical records is a limitation of the study. Furthermore, future studies should also aim to include more detailed information about sport experience, such as amount of practice hours per week. Moreover, the current results apply to eye–limb skill sports, but these findings might not be generalisable to sports that require less eye–hand coordination, such as track, swimming, dance, or cycling. Though the sports sampled in the present study are among the ones with greater rates of concussion (Meehan 3rd & Bachur, 2009), future studies should investigate whether the same findings are true for sports that rely less upon eye–hand coordination. Also, future studies that implement longitudinal approaches would provide additional insight into the underlying recovery mechanisms within participants and the links to re-injury and potential long-term risks.

Conclusions

The results of the present study indicate an important role of sport-related visuomotor experience in complex motor skill recovery in youth with a history of concussion. Youth with a concussion history and higher levels of sport-related visuomotor experience (7 years or more) had quicker CMI recovery times (around 12 months) compared to their peers with less sport-related visuomotor experience (around 30 months). We suggest that this faster CMI recovery after a concussion may be linked to a greater motor skill-related neurological "reserve" acquired from participating in eye–limb coordination sports and allowing for behavioural performance compensation. These findings may underline a difference between assessments of readiness to return to play using current clinical assessment techniques and true time of sport-relevant skill recovery post-concussion.

Acknowledgements

The authors wish to thank Marco Di Palma and the other volunteers who assisted with data acquisition, Denyse Pilkington and David Albines for coordinating the testing and volunteer training, and Saihong Sun for computer programming support.

Funding

Funding for this research was provided by the Canadian Institutes of Health Research operating grant #125915(LS), and the Donald Sanderson Memorial Trust.

Disclosure statement

No potential conflict of interest was reported by the authors.

Supplemental data

Supplemental data for this article can be accessed here (http://dx.doi.org/10.1080/17461391.2019.1584249).

References

Albines, D., Granek, J. A., Gorbet, D. J., & Sergio, L. E. (2016). Bimanual coordination development Is Enhanced in young females and Experienced athletes. *Journal of Motor Learning and Development*, *4*(2), 274–286.

Black, A. M., Cat, C., Sergio, L. E., & Macpherson, A. K. (2016). The Epidemiology of concussions: Number and nature of concussions and time to recovery Among Female and Male Canadian varsity athletes 2008 to 2011. *Clinical Journal of Sport*, *27*(1), 52–56.

Brown, J. A., Dalecki, M., Hughes, C., Macpherson, A. K., & Sergio, L. E. (2015). Cognitive-motor integration deficits in young adult athletes following concussion. *BMC Sports Science, Medicine and Rehabilitation*, *7*(1), 25.

Chiang Colvin, A., Mullen, J., Lovell, M. R., Vereeke West, R., Collins, M. W., & Groh, M. (2009). The role of concussion history and gender in recovery from soccer-related concussion. *The American Journal of Sports Medicine*, *37*(9), 1699–1704.

Collins, C. L., Fletcher, E. N., Fields, S. K., Kluchurosky, L., Rohrkemper, M. K., Comstock, R. D., & Cantu, R. C. (2014). Neck strength: A protective factor reducing risk for concussion in high school sports. *The Journal of Primary Prevention*, *35*(5), 309–319.

Covassin, T., Schatz, P., & Swanik, C. B. (2007). Sex differences in neuropsychological function and post-concussion symptoms of concussed collegiate athletes. *Neurosurgery*, *61*(2), 345–351.

Dalecki, M., Albines, D., Macpherson, A., & Sergio, L. E. (2016). Prolonged cognitive–motor impairments in children and adolescents with a history of concussion. *Concussion*, *1*(3), CNC14.

Davenport, E. M., Whitlow, C. T., Urban, J. E., Espeland, M. A., Jung, Y., Rosenbaum, D. A., … Maldjian, J. A. (2014). Abnormal white matter integrity related to head impact exposure in a season of high school varsity football. *Journal of Neurotrauma*, *31*(19), 1617–1624.

Di, X., Zhu, S., Jin, H., Wang, P., Ye, Z., Zhou, K., … Rao, H. (2012). Altered resting brain function and structure in professional badminton players. *Brain Connectivity*, *2*(4), 225–233.

Gorbet, D. J., & Sergio, L. E. (2007). Preliminary sex differences in human cortical BOLD fMRI activity during the preparation of increasingly complex visually guided movements. *European Journal of Neuroscience*, *25*(4), 1228–1239.

Gorbet, D. J., & Sergio, L. E. (2009). The behavioural consequences of dissociating the spatial directions of eye and arm movements. *Brain Research*, *1284*, 77–88.

Gorbet, D. J., & Sergio, L. E. (2016). Don't watch where you're going: The neural correlates of decoupling eye and arm movements. *Behavioural Brain Research*, *298*(Pt B), 229–240.

Granek, J. A., & Sergio, L. E. (2015). Evidence for distinct brain networks in the control of rule-based motor behavior. *Journal of Neurophysiology*, *114*(2), 1298–1309.

Guskiewicz, K. M., Marshall, S. W., Bailes, J., McCrea, M., Cantu, R. C., Randolph, C., & Jordan, B. D. (2005). Association between recurrent concussion and late-life cognitive impairment in retired professional football players. *Neurosurgery*, *57*, 719–726.

Guskiewicz, K. M., McCrea, M., Marshall, S. W., Cantu, R. C., Randolph, C., Barr, W., … Kelly, J. P. (2003). Cumulative effects associated with recurrent concussion in collegiate football players: The NCAA concussion study. *JAMA: the Journal of the American Medical Association*, *290*, 2549–2555.

Hawkins, K. M., Sayegh, P., Yan, X., Crawford, J. D., & Sergio, L. E. (2013). Neural activity in superior parietal cortex during rule-based visual-motor transformations. *Journal of Cognitive Neuroscience*, *25*(3), 436–454.

Hurtubise. (2016). The effect of concussion history on cognitive-motor integration in elite hockey players. *Concussion*. doi:10.2217/cnc-2016-0006

Karlin, A. M. (2011). Concussion in the pediatric and adolescent population: "different population, different concerns". *PM & R: the Journal of Injury, Function, and Rehabilitation*, *3*, 369–379.

Kissick, J., & Johnston, K. M. (2005). Return to play after concussion: Principles and practice. *Clinical Journal of Sport Medicine*, *15*(6), 426–431.

Lenroot, R. K., & Giedd, J. N. (2010). Sex differences in the adolescent brain. *Brain and Cognition*, *72*, 46–55.

Lubans, D. R., Morgan, P. J., Cliff, D. P., Barnett, L. M., & Okely, A. D. (2010). Fundamental movement skills in children and adolescents. *Sports Medicine*, *40*(12), 1019–1035.

Mainwaring, L., Pennock, K. M. F., Mylabathula, S., & Alavie, B. Z. (2018). Subconcussive head impacts in sport: A systematic review of the evidence. *International Journal of Psychophysiology*, *132*, 39–54.

McAllister, T. W., Sparling, M. B., Flashman, L. A., Guerin, S. J., Mamourian, A. C., & Saykin, A. J. (2001). Differential working memory load effects after mild traumatic brain injury. *Neuroimage*, *14*, 1004–1012.

McCrory, P., Meeuwisse, W. H., Aubry, M., Cantu, R. C., Dvorak, J., Echemendia, R. J., … Raftery, M. (2013). Consensus statement on concussion in sport—the 4th International Conference on concussion in sport held in Zurich, November 2012. *PM&R*, *5*(4), 255–279.

McCrory, P., Meeuwisse, W., Dvorak, J., Aubry, M., Bailes, J., Broglio, S., … Castellani, R. J. (2017). Consensus statement on concussion in sport—the 5th international conference on concussion in sport held in Berlin, October 2016. *British Journal of Sports Medicine*. doi:10.1136/bjsports-2017-097699

Meehan 3rd, W. P., & Bachur, R. G. (2009). Sport-related concussion. *Pediatrics*, *123*, 114–123.

Park, I. S., Lee, K. J., Han, J. W., Lee, N. J., Lee, W. T., & Park, K. A. (2009). Experience-dependent plasticity of cerebellar vermis in basketball players. *The Cerebellum*, *8*(3), 334.

Paus, T. (2005). Mapping brain maturation and cognitive development during adolescence. *Trends in Cognitive Sciences*, *9*(2), 60–68.

Sayegh, P. F., Hawkins, K. M., Neagu, B., Crawford, J. D., Hoffman, K. L., & Sergio, L. E. (2014). Decoupling the actions of the eyes from the hand alters beta and gamma synchrony within SPL. *Journal of Neurophysiology*, *111*(11), 2210–2221.

Sergio, L. E., Dalecki, M., Hurtubise, J., Brown, J., Gorbet, D., Hughes, C., & Macpherson, A. (2017). Measuring cognitive-motor integration to detect prolonged performance declines post-concussion. *British Journal of Sports Medicine*, *51*(11), A41–A41.

Slobounov, S., Gay, M., Johnson, B., & Zhang, K. (2012). Concussion in athletics: Ongoing clinical and brain imaging research controversies. *Brain Imaging and Behavior*, *6*, 224–243.

Slobounov, S., Sebastianelli, W., & Simon, R. (2002). Neurophysiological and behavioral concomitants of mild brain injury in collegiate athletes. *Clinical Neurophysiology*, *113*(2), 185–193.

Slobounov, S. M., Zhang, K., Pennell, D., Ray, W., Johnson, B., & Sebastianelli, W. (2010). Functional abnormalities in normally appearing athletes following mild traumatic brain injury: A functional MRI study. *Experimental Brain Research*, *202*, 341–354.

Sollmann, N., Echlin, P. S., Schultz, V., Viher, P. V., Lyall, A. E., Tripodis, Y., … Forwell, L. A. (2018). Sex differences in white matter alterations following repetitive subconcussive head impacts in collegiate ice hockey players. *Neuroimage: Clinical*, *17*, 642–649.

Solomon, G. S., Kuhn, A. W., Zuckerman, S. L., Casson, I. R., Viano, D. C., Lovell, M. R., & Sills, A. K. (2016). Participation in Pre–high School Football and neurological, Neuroradiological, and Neuropsychological findings in later life: A study of 45 retired National Football League players. *The American Journal of Sports Medicine*, *44*(5), 1106–1115.

Tierney, R. T., Sitler, M. R., Swanik, C. B., Swanik, K. A., Higgins, M., & Torg, J. (2005). Gender differences in head-neck segment dynamic stabilization during head acceleration. *Medicine And Science in Sports And Exercise*, *37*(2), 272–279.

Tremblay, S., De Beaumont, L., Henry, L. C., Boulanger, Y., Evans, A. C., Bourgouin, P., … Lassonde, M. (2013). Sports concussions and aging: A neuroimaging investigation. *Cerebral Cortex (New York, N.Y.: 1991)*, *23*, 1159–1166.

Tremblay, S., Henry, L. C., Bedetti, C., Larson-Dupuis, C., Gagnon, J. F., Evans, A. C., … De Beaumont, L. (2014). Diffuse white matter tract abnormalities in clinically normal ageing retired athletes with a history of sports-related concussions. *Brain: a Journal of Neurology*, *137*, 2997–3011.

Wang, J., Lu, M., Fan, Y., Wen, X., Zhang, R., Wang, B., … Wang, J. (2016). Exploring brain functional plasticity in world class gymnasts: A network analysis. *Brain Structure and Function*, *221*(7), 3503–3519.

Zhang, K., Johnson, B., Pennell, D., Ray, W., Sebastianelli, W., & Slobounov, S. (2010). Are functional deficits in concussed individuals consistent with white matter structural alterations: Combined FMRI & DTI study. *Experimental Brain Research*, *204*, 57–70.