Visuomotor adaptation learning not affected by repeated sport-related concussion

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Abstract
Sports-related concussions (SRC) have been associated with emotional, cognitive, and affective symptoms including a negative impact on motor-based learning. However, no study has assessed the impact of SRC on cerebellar-based motor learning. Cerebellar-based motor learning was assessed in three different groups of athletes with different SRC history: athletes with no history of SRC, athletes in the acute stage of SRC (within two weeks of injury), and athletes in the chronic stage of SRC (over one year after injury). We used a visuomotor adaptation task (VAT) to measure both explicit strategy-based learning and implicit error-based learning. We found that there was no difference in cerebellar dependent motor learning in SRC and non-SRC athletes. These findings suggest that the cerebellum may be more resilient to damage from SRCs than the motor cortex.

Keywords
Concussion, sports-related concussion, mTBI, repetitive mTBI, neuropsychology

Introduction
Every year, between 1.6 to 3.8 million SRCs occur in sports-related and recreational activities.\(^1\) SRCs have a wide range of debilitating symptoms, including emotional, cognitive, and affective symptoms that are typically worse closer to the time of injury but can have widely varying timelines of recovery.\(^2,3\) Despite the overwhelming heterogeneity in this patient population, increasing evidence suggests the motor system may be particularly sensitive to repeated concussive events\(^4-7\) with some of the earliest clinical indications of chronic traumatic brain injuries being motor symptoms\(^5\) and motor learning deficits being even more sensitive to injury than motor impairments detected with self-report measures and standard SRC evaluations.\(^9-12\)

Critically different forms of motor learning tasks, such as learning new motor behaviors or adjusting previously learned ones to account for changes in our environment, require the operation of multiple, distinct learning processes, each of which is governed by different neural substrates like the cerebellum or M1.\(^13,14\) Previous work in concussed athletes with no obvious motor control deficits showed impairments in motor learning tasks that require learning new motor patterns and rely heavily on M1-dependent processes, such as the acquisition learning of the Serial Reaction Time Task (SRTT)\(^7,12,15\) and retention learning of the Sequential Visual Isometric Pinch Task (SVIPT).\(^6,10,16\) Despite evidence of repeated SRCs affecting the learning of new motor patterns, there is less evidence for whether SRCs affect other forms of motor learning that rely heavily on cerebellar-dependent processes such as adjusting movements to account for changes in our environment. A previous study found that cerebellar learning is both slower and less

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accurate in concussed individuals compared to those without a history of SRC.\textsuperscript{11} The visuomotor adaptation task (VAT) is partially based on implicit motor learning, which is a slow non-conscious form of cerebellar-based learning.\textsuperscript{18} Here we aim to understand the effect of different phases of SRC recovery (i.e., acute: < 2 weeks post-injury and chronic: > 1 year post-injury), on a cerebellar-dependent form of error-based learning, i.e., the VAT.

We predicted that visuomotor adaptation acquisition would be impaired in concussed athletes compared to non-SRC athletes and learning would be negatively correlated with the number of previously sustained SRCs. We also predicted that motor learning would be more impaired in athletes in the acute-phase of recovery compared to athletes in the chronic-phase of recovery.

**Methods**

**Participants**

The study was approved by the Johns Hopkins School of Medicine and Walter Reed Army Institute of Research Institutional Review Boards in accordance with the declaration of Helsinki as part of the Behavioral and Neurophysiological Markers of Concussion (BANCO) study. Sixty-six athletes were recruited from Johns Hopkins University contact sports (Football, Wrestling, Lacrosse, Water Polo, Soccer, and Field Hockey) and non-contact sports (Track and Field, Swimming, Fencing, and Tennis) programs. Fifty-five student athletes completed the study (41 men/13 women, 11 left-handed/34 right-handed), 2 failed the screening and 9 dropped out before completion of the study (Table 1).

Based on a questionnaire interview on prior SRC history, the athletes were sorted into three non-overlapping groups.\textsuperscript{6} Acute SRCs were diagnosed by the team physician using the SCAT-3 criteria and any SRCs that occurred during university years were based on medical records. SRCs that occurred prior to university years were determined by in-depth interview done between the examiner and participant recounting any previous SRC history that lasted approximately 20 min (specific questions in this interview can be viewed in.\textsuperscript{6} Following the grouping conventions of similar studies, the groups were defined as follows.\textsuperscript{6}:

1. Non-concussed group (NonCon): athletes who reported no history of concussion (n = 22)
2. Chronically-concussed group (Chronic): athletes that reported sustaining a concussion more than 1 year prior to study participation (n = 21).
3. Acutely-concussed group (Acute): athletes that reported sustaining a concussion less than two weeks prior to study participation (n = 12).

**Experimental design**

Participants were seated facing a horizontally-oriented computer monitor (47 × 30 cm) holding a stylus (cursor movement was controlled by the stylus) in their dominant hand above a digitized touchpad. The monitor was placed above the touchpad occluding participants’ vision of their own hand for the entirety of the experiment. Participants began the task with their hand holding the stylus inside a 5 mm starting circle located at the center of the screen. Once inside the starting circle for 1 s, a 7 mm green target would appear 70 mm from the center on a visual landmark that ringed the edge of the tablet screen. The visual landmarks that ringed the screen consisted of consecutively labeled numbers located 5.625° apart from one another (ranging from 31 to −31 relative to the green target) and were used for verbally reporting aim strategy (Fig. 1A). Once the green target appeared, participants were instructed to perform a ballistic center-out reaching task in a slicing movement through the green target (i.e., reach through the target, do not stop at the target). Importantly,

| Measures | Group | P Values | Group | P Values | Group | P Values |
|----------|-------|----------|-------|----------|-------|----------|
| Sport    | NonCon | Chronic | Acute | N/A |
| FB, 2 S, 7 TF, | 1 F, 2 FH, I | 2 B, 2 LX, | I V, 1 WP, | V, 6 WP, 2 WR, | 6 WR |
| Sex      | 11 M   | 16 M    | 11 M  | 1 F |
| Age      | 19.82 (0.27) | 20.32 (0.3) | 20.67 (0.38) | 0.07 |
| GPA      | 3.36 (0.08) | 3.32 (0.08) | 3.41 (0.1) | 0.774 |
| HART     | 23.09 (0.98) | 24.29 (0.75) | 23.33 (1.25) | 0.784 |
| MFI      | 41.53 (2.2) | 38.74 (2.48) | 44.17 (4.96) | 0.654 |
| BC-PSI   | 4.41 (1.05) | 2.68 (0.69) | 9.75 (1.33) | 0.007* |
| STAI     | 62.47 (2.93) | 61.26 (3.48) | 61.33 (2.46) | 0.796 |
| MIDAS    | 0.94 (0.6) | 1.63 (0.68) | 5.83 (1.71) | 0.002* |
| HIT-6    | 45 (7.13) | 45.39 (7.96) | 46.08 (2.27) | 0.713 |
| PSQI     | 5.18 (0.45) | 4.79 (0.38) | 5.33 (0.72) | 0.9 |
| ESS      | 7.88 (0.65) | 7.16 (0.64) | 6.33 (1.16) | 0.185 |
visualization of the cursor disappeared after initiating the trial movement and then only reappeared as a red cursor once the participant’s hand passed 70 mm to indicate the participant’s endpoint movement relative to the cued green target. If the cursor overlapped with the green target circle a “ding” feedback sound was played indicating the target was successfully acquired. If the cursor did not overlap with the target circle, a “buzz” sound was played indicating the target was missed. To maintain consistent ballistic movements, if participants took longer than 275 ms to complete the outward movement, an audio voice recording saying “too slow” was played. If the participants completed the outward movement in less than 175 ms, an audio recording saying “too fast” was played. To facilitate motivation, on trials where participants successfully ‘hit’ the target within the correct movement time range, they were awarded a point. After each trial, participants were instructed to return to the starting circle position in the middle of the screen.

For each reaching trial, the green target would appear in one of 8 possible radial targets: 0°, 45°, 90°, 135°, 180°, 225°, 270°, or 305° from horizontal. Target order was randomized so that every epoch of 8 trials contained one presentation of each target.

The paradigm was divided into five distinct blocks of varying number of trials (Fig. 1B). In the first block (B1), participants completed 65 trials in a baseline condition, where the participants were instructed to simply reach towards the green target. In the second block (B2), participants completed another 24 trials in the baseline condition while also being asked to verbally report the visual landmark they were aiming their reach toward before initiating the movement. B1 and B2 were collectively known as the pre-rotation period. In the third block (B3), a constant perturbation of 45° clockwise rotation away from the target endpoint on screen was introduced. Participants completed 160 trials in this rotation condition while still verbally reporting their aim before initiating the reach movement (B3 is known as the adaptation block and is used to assess the learning of the 45° rotation). In the fourth block (B4), the perturbation was removed, and the participants completed 40 trials where the endpoint feedback and aiming landmarks were removed from the display (B4 is known as the retention block (post 1) and used to assess the forgetting of the 45° rotation). In the fifth block (B5), participants completed 40 trials where endpoint feedback and visual landmarks were restored (B5 is known as the wash-out block (post 2) and used to assess active unlearning of the environmental perturbation).

### Data analysis

For each trial, we computed the Reach Angle (RA), calculated as the distance between a participant’s endpoint and the green target circle. Larger RA values are indicative of a larger reaching error (i.e., worse performance). RA was then further subdivided into its explicit (conscious strategy-based learning) and implicit (subconscious error-based learning) components. Explicit aim (EA) was defined as the distance between the visual landmark reported by the participant and the green target circle. Implicit aim (IA) was defined as the difference between RA and Explicit aim (Figure 1).

Performance changes on the VAT was quantified into effects on acquisition, retention, and unlearning. Acquisition, defined as the speed of adaptation to the perturbation, was defined here as the first block at the beginning of block 3. Retention, defined as longer lasting errors after the perturbation was removed, was defined here as the Reach Angle, Explicit Aim, and Implicit Aim at the beginning of block 4. To analyze acquisition and retention, the start and end of each block placed into bins of 8 trials each. The average across every block was also analyzed for difference. To calculate our difference scores, we subtracted the reach angle/explicit aim/implicit aim at the beginning of each block from the reach angle/explicit aim/implicit aim at the end of each block.

Reach Angle, Explicit Aim, Implicit Aim, acquisition, retention and difference scores were analyzed using separate one-way ANOVAs with between subject factor GROUP (NoCon, Acute, Chronic). Tukey’s Post hoc analysis was performed with two-tailed t-tests when appropriate. Kendall’s Tau was used to correlate the number of SRCs with each of our behavioral measures.

Participants whose trial averages were greater than three standard deviations from the group mean were removed as outliers. All data are given as means ± SEM. Effects were considered significant if p < 0.05.

### Results

**SRC history does not alter adaptation of reach in binned trials**

There were no SRC individuals in the non-concussed group. There was an average of 2.21 SRCs (SE = 0.06) in the chronically concussed group, and an average of 2.33 SRCs (SE = 0.11) in the acutely concussed group. We assessed learning curves for all participants in the study. After collapsing across all perturbation trials, there was no significant difference in reach angle there were no significant differences between groups for either of the baseline block (Baseline No Report: F(1, 46) = 3.056, p = .087), Baseline with Report: F(1, 46) = .627, p = .433), start of rotation (F(1, 46) = 1.068, p = .307), end of rotation (F(1, 46) = .484, p = .49), start of aftereffect (F(1, 46) = 3.187, p = .081), end of aftereffect (F(1, 46) = 1.347, p = .252), start of washout (F(1, 46) = 1.002, p = .322), or end of washout (F(1, 46) = .01, p = .919) [Fig2A]. There was no significant difference in the difference scores at the start and end of baseline (F(1, 46) = 0.379, p = .58), the start and end of rotation (F(1, 46) = .776, p = .383), the start and end of aftereffect (F(1, 46) = 0.468,
Comparing explicit aim there were no significant differences between groups at the start of baseline and report ($F(1, 44) = 0.97, p = .33$), end of baseline and report ($F(1, 44) = .048, p = .828$), start of rotation and report ($F(1, 44) = 2.209, p = .144$), or end of rotation and report ($F(1, 44) = 1.937, p = .171$)[Fig 2B]. There was no significant difference

Figure 1. A) this figure represents a visuomotor adaptation task with a −45 degree perturbation with the numbers for reported aim in the outer ring of the circle. The blue area represents explicit error and the red area represents implicit error B) This figure represents the correct reach angle in relation to the displayed target by block. The y-axis represents the Reach Angle compared to the displayed target. The x-axis represents the trial number.
in the difference scores at the start and end of baseline ($F(1, 44) = 0.621, p = .435$) or at the start and end of rotation ($F(1, 44) = 0.192, p = .663$).

There was no significant difference in implicit aim between groups at the start of baseline and report ($F(1, 46) = 0.143, p = .707$), end of baseline and report ($F(1, 46) = 0.006, p = .939$), start of rotation and report ($F(1, 46) = 0.059, p = .81$), and end of rotation and report ($F(1, 46) = 1.327, p = .255$). There was no significant difference in the difference scores at the start and end of baseline ($F(1, 46) = 0.121, p = .73$) or at the start and end of rotation ($F(1, 46) = 0.509, p = .479$).

There were no differences between groups across all trials in the perturbation block for Reach Angle ($F(1, 53) = 1.00, p = .322$), Explicit Aim ($F(1, 44) = 0.526, p = .472$), nor Implicit Aim ($F(1, 46) = 0.554, p = .461$).

There was also no difference in ratio between groups. There was no difference at the Start of Baseline and Report ($F(1, 44) = 1.22, p = .276$), the End of Baseline and Report ($F(1, 44) = 1.31, p = .258$), the Start of Rotation and Report ($F(1, 44) = 3.10, p = .086$), or the End of Rotation and Report ($F(1, 44) = 1.64, p = .207$).

Using a simple linear regression, we found there was no relationship between the number of SRCs and the reach angle ($F(1, 46) = .162, p = .689$), explicit aim ($F(1, 44) = .002, p = .961$), and implicit aim ($F(1, 46) = .563, p = .457$).

**Discussion**

**Summary**

When investigating changes in visuomotor adaptation, we found no significant differences in performance for reach angle, explicit aim, or implicit aim between our non-concussed, chronically-concussed, and acutely-concussed athletes. Visuomotor adaptation across the three groups looked nearly identical for metrics of its acquisition, retention, and unlearning. In addition, we saw no significant correlations between prior SRC history and any metrics of motor learning or control. This is in contrast to other findings in the same cohort, where differences in motor skill learning or measures of cortical latency based on SRC history were observed. Overall, our findings suggest that visuomotor adaptation was not affected by SRC, either in its acute or chronic phases of recovery.

**Sport related concussions may selectively affect corticomotor pathways**

While other research has shown motor learning of new motor behaviors such as SRTT and SVIPT is affected after a SRC, here we show no motor learning deficits during a visuomotor adaptation task in our concussed athletes. Other studies in patients with cerebellar damage such as spinocerebellar ataxia or cerebellar stroke found that visuomotor adaptation was negatively affected. This lack learning impairment for visuomotor adaptation may suggest that repeated SRCs may have a stronger negative impact on motor learning tasks that are highly-dependent on M1 processes whereas more cerebellar depending learning processes are spared. One possibility for this is that the cerebellum (due to its location and size) may be less prone to impact injury than the motor cortex. It could be that SRCs have a stronger negative impact for learning metrics involving movement speed or sequencing over accuracy. For example, the previously mentioned motor learning tasks, SVIPT and SRRT, which have detected differences in motor learning in concussed individuals both utilize improvements in speed and sequencing in...
their tasks. In contrast, the VAT clamps the speed for each trial and only looks at changes in accuracy, it also lacks any sequence-learning component as the target location for each trial is randomized.

Alternately, our null results may suggest that our task may not have been sufficiently challenging to detect any differences in our participants’ abilities. Motor deficits might be mitigated by the level of skill expertise of the affected individuals, suggesting that such experience imparts resiliency. It is possible, had the introduced perturbation been more difficult (i.e., larger rotation) and further challenged our participants’ ability, learning deficits would have emerged. Interestingly for the SVIPT, which was performed in this same cohort of athletes as part of the BANCO study, impairments in motor performance were only evident in the second day of motor training, suggesting that concussed athletes retained less of what they learned across days. Interestingly, prior research indicates that sleep may also be negatively affected in concussed athletes as part of the BANCO study, impairments in motor ability, learning deficits might have emerged. Interestingly for the SVIPT, which was performed in this same cohort of athletes as part of the BANCO study, impairments in motor performance were only evident in the second day of motor training, suggesting that concussed athletes retained less of what they learned across days. Interestingly, prior research indicates that sleep may also be negatively affected in concussed athletes which can play an important role in the consolidation of motor memories. Here retention was only assessed immediately following the perturbation. It is also possible had participants returned the following day to assess savings across sessions, differences between motor performance metrics may have emerged.

Our results are also in contrast with other studies exploring hand eye coordination where authors reported slower movement time and poorer accuracy for target reaching in a task where concussed athletes were required to perform a horizontal plane transformation of their movements. Critically, these studies were focused on assessing cognitive-motor integration, not motor learning as was done here. Second, in the present study, movement time for the VAT was fixed at 275 ms whereas in the transformation of hand-eye coordination task, movements were allowed to be much slower (i.e., on the order 700 ms), allowing for online correction of movements, a metric that is perhaps more sensitive to injury. Finally, the athlete demographic between these studies and our own differ. Whereas in the Dalecki et al. and Hurtubise et al. studies, athletes were recruited from a pediatric population (i.e., 17-year and younger), our study investigated cerebellar learning deficits in college-aged athletes. Thus, it possible that the older age and further brain development of our cohort athletes offered an additional layer of protection of motor deficiencies found in the younger athletes.

Overall, unlike M1, there was no difference in the visuomotor adaptation between participants without SRCs and participants with SRCs. Future research should investigate whether varying the type of visuomotor adaptation task or the age of the participants affects the extent of a SRC-related impairment.

Declaration of conflicting interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethical approval
The study was approved by the Johns Hopkins School of Medicine and Walter Reed Army Institute of Research Institutional Review Boards in accordance with the Declaration of Helsinki.

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References
1. Langlois JA, Rutland-Brown W and Wald MM. The epidemiology and impact of traumatic brain injury: a brief overview. J Head Trauma Rehabil 2006; 21: 375–378.
2. Kay T, Newman B, Cavallo M, et al. Toward a neuropsychological model of functional disability after mild traumatic brain injury. Neuropsychology 1992; 6: 371–384.
3. Rao V, Syeda A, Roy D, et al. Neuropsychiatric aspects of concussion: acute and chronic sequelae. Concussion 2017; 2: 1.
4. Stokes W, Runnalls K, Choynowski J, et al. Altered corticomo-tor latencies but normal motor neuroplasticity in concussed athletes. J Neuropsychol 2020; 123: 1600–1605.
5. Meehan SK, Mirdamadi JL, Martini DN, et al. Changes in Cortical Plasticity in Relation to a History of Concussion during Adolescence. Front Hum Neurosci 2017; 11: 5.
6. Cantarero G, Choykowski J, St Pierre M, et al. Repeated concussions impair behavioral and neurophysiological changes in the motor learning system. Neurorehabil Neural Repair 2020; 34: 804–813.
7. De Beaumont L, Tremblay S, Poirier J, et al. Altered bidirectional plasticity and reduced implicit motor learning in concussed athletes. Cerebral Cortex (New York, N.Y.: 1991) 2012b; 22: 112–121.
8. Rabadi MH. The cumulative effect of repetitive concussion in sports. Clinical Journal of Sport Medicine 2001; 11(3): 194–198.
9. De Beaumont L, Henry LC and Gosselin N. Long-term functional alterations in sports concussion. Neurosurg Focus 2012a; 33: E8: 1–7.
10. Cantarero G, Lloyd A and Celnik P. Reversal of long-term potentiation-like plasticity processes after motor learning disrupts skill retention. J Neurosci 2013b; 33: 12862–12869.
11. Sergio LE, Gorbet DJ, Adams MS, et al. The Effects of Mild Traumatic Brain Injury on Cognitive-Motor Integration for Skilled Performance. Front Neurol 2020; 11. https://doi.org/10.3389/fneur.2020.541630.
12. De Beaumont L, Tremblay S, Henry LC, et al. Motor system alterations in retired former athletes: the role of aging and concussion history. BMC Neurol 2013; 13: 109.
13. Hardwick RM, Rottschy C, Miall RC, et al. A quantitative meta-analysis and review of motor learning in the human brain. Neuroimage 2013; 67: 283–297.
14. De Zeeuw CI and Ten Brinke MM. Motor learning and the cerebellum. Cold Spring Harbor Perspect Biol 2015; 7: 9.
15. Chowdhury N, Livesey E and Harris J. Individual differences in intracortical inhibition during behavioural inhibition. *Neuropsychologia* 2019; (124): 55 – 565.
16. Spampinato D and Celnik P. Multiple Motor Learning Processes in Humans: Defining Their Neurophysiological Bases. *Neuroscientist* 2021; 27: 246-267.
17. Liew S L, Thompson T, Ramirez J, et al. Variable neural contributions to explicit and implicit learning during visuomotor adaptation. *Front Neurosci* 2018; 12: 610.
18. Kleynen M, Braun SM, Bleijlevens MH, et al. Using a delphi technique to seek consensus regarding definitions, descriptions and classification of terms related to implicit and explicit forms of motor learning. *PLoS ONE* 2014; 9: e100227.
19. Galea JM, Vazquez A, Pasricha N, et al. Dissociating the roles of the cerebellum and motor Cortex during adaptive learning: the motor Cortex retains what the cerebellum learns. *Cerebral Cortex (New York. NY)* 2011; 21: 1761–1770.
20. Taylor JA, Krakauer JW and Ivry RB. Explicit and implicit contributions to learning in a sensorimotor adaptation task. *J Neurosci* 2014; 34: 3023–3032.
21. Vaca-Palomares I, Díaz R, Rodríguez-Labrada R, et al. Spinocerebellar ataxia type 2 neurodegeneration differentially affects error-based and strategic-based visuomotor learning. *Cerebellum (London. England)* 2013; 12: 848–855.
22. Werner S, Bock O, Gizewski ER, et al. Visuomotor adaptive improvement and aftereffects are impaired differentially following cerebellar lesions in SCA and PICA territory. *Exp Brain Res* 2010; 201: 429–439.
23. Beckwith JG, Zhao W, Ji S, et al. Estimated brain tissue response following impacts associated with and without diagnosed concussion. *Ann Biomed Eng* 2018; 46: 819–830.
24. Al-Sharman A and Siengsukon CF. Sleep enhances learning of a functional motor task in young adults. *Phys Ther* 2013; 93: 1625–1635.
25. Dalecki M, Albines D, Macpherson A, et al. Prolonged cognitive-motor impairments in children and adolescents with a history of concussion. *Concussion (London. England)* 2016; 1: 3 CNC14.
26. Hurtubise J, Gorbet D, Hamandi Y, et al. The effect of concussion history on cognitive-motor integration in elite hockey players. *Concussion (London. England)* 2016; 1: 3 CNC17.
27. Cantarero G, Tang B, O’Malley R, et al. Motor learning interference is proportional to occlusion of LTP-like plasticity. *J Neurosci* 2013a; 33: 4634–4641.