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Long-term Effects of Adolescent Sport Concussion Across the Age Spectrum

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Abstract

Background: Research in sport concussion has grown precipitously over the previous decade due to increased scientific interest, as well as the media and political spotlight that has been cast on this injury. However, there is a dearth of literature regarding the long-term (>1 year post concussion) effects of adolescent concussion on cognitive and motor performance of high school athletes.

Purpose: The purpose of this study was to evaluate the potential for long-term effects of concussion sustained during high school on cognitive and motor performance across the lifespan.

Study Design: Cross-sectional study.

Methods: Adults with (n=30) and without a concussion history (n=53) were recruited in younger (18–30 years old; n=43), middle aged (40–49 years; n=18), and older (60+ years; n=22) age groups. Each participant completed a computerized neurocognitive assessment and continuous tracking and discrete temporal auditory tasks with the hand and foot. Root mean squared error and timing variability were derived from the tracking and temporal auditory tasks, respectively. Data were analyzed by regression analyses for each recorded variable.

Results: There were significant age effects on neurocognitive task, continuous tracking task, and discrete auditory timing task performance (p 's < 0.05). There were no concussion history or interaction (concussion history by age) effects for performance on any task (p 's > 0.05).

Conclusion: While longitudinal investigations are still needed, this cross-sectional study failed to identify any observable effect of adolescent concussion history on cognition or motor performance with age.

Clinical Relevance: There is a paucity of concussion history literature addressing the largest population of athletes participating in sport, the high school athlete. The results herein begin to address the possible effects of an adolescent concussion history on cognitive and motor performance across the age spectrum.

Keywords

Chronic; High School; Force Control; Neurocognitive Test

Introduction

Research in sport concussion has grown precipitously over the previous decade due to increased scientific interest, as well as the media and political spotlight that has been cast on this injury. The findings of multiple investigations have led to an evolving understanding of injury incidence and the acute and chronic effects of concussion(s). For example, traditional incidence rates of concussion were once thought to approach 250,000 cases annually²⁵, though advances in concussion education⁵⁵ and state legislation²⁷ have resulted in increased injury reporting³⁶. More recent reports now suggest that over 250,000 sport concussions occur each year, in the subset of adolescent athletes seeking care in the Emergency Department setting alone².

Additionally, a growing body of evidence suggests that a concussion can no longer be perceived as a transient injury^{6, 13, 19, 43, 48, 53, 56}. Evidence suggests that in the retired, professional athlete population, individuals with longer lifetime exposure to sport-associated head trauma and the concussions associated with it, may have increased rates of depression²⁹ and dementia²⁸, as well as the potential development of chronic traumatic encephalopathy^{6, 48, 53}. In contrast, there is little research available on former high school athletes, the larger population of former athletes. Of the 7.7 million high school students participating in athletics each year, only a small percentage progress to the professional level, yet male and female high school athletes have an annual concussion incidence rate of 0.25 (per 1000 athletic exposures)^{37, 41}. Despite high school athletes representing the largest cohort of at risk athletes, there is a considerable gap in the concussion literature evaluating potentially persistent cognitive and motor performance alterations beyond the acute recovery period in this population.

Previous work in young adults with a concussion history has demonstrated both cognitive and motor alterations well beyond clinical recovery from concussion. These altered measures include gait, balance, and neural function^{12, 14, 19, 21, 43, 56}. Electrophysiological alterations have been observed from 30 months to 30 years post-concussion^{12, 19, 20, 54}, providing empirical evidence of lasting differences between individuals with and without a concussion history. The clinical implications of how these differences may alter daily life for individuals with an adolescent concussion history, defined here as history of concussion(s) occurring prior to age 19, are poorly characterized and warrant investigation.

It has been proposed that concussion may result in an accelerated rate of cognitive and motor decline with age¹⁰. This idea is inspired by other accepted behavioral and environmental factors known to have a negative influence on neurocognitive

performance^{44, 45}, beyond the well-established natural decline in cognition and motor control associated with aging³⁵. Considering the underrepresentation of adolescent concussion history in the literature, there is uncertainty if this theory applies to all levels of concussion history.

Therefore, the purpose of this study was to compare measures of cognitive and motor performance between individuals with and without an adolescent concussion history, across ages. Based on previous findings, we hypothesize that individuals with an adolescent concussion history will perform worse on cognitive and motor tasks compared to matched controls, and the magnitude of these differences will increase with age.

Methods

Participants

Eighty-three participants completed this study. Potential participants were excluded if they reported a concussion after 18 years of age. Participants were recruited in six groups based on their self-reported concussion history and age (18–30, 40–50, 60+ years). Based on published⁴³ and pilot data of the youngest age group effect sizes, a sample size calculation indicated 120 total participants, evenly distributed across the six groups. While we fell short of this goal, model-2 regression effect size calculations from the current data suggest a sample size over 1100 participants would be needed to reach significance ($\alpha < 0.05$) at a power of .80 across all tasks. Participants were recruited through local and university newspapers, as well as the university's clinical research website. Each participant completed a study questionnaire, a computerized concussion assessment, and continuous tracking and discrete temporal motor control tasks with the hand and foot during a single laboratory-based testing session. The Medical School Institutional Review Board at the University of Michigan approved this study and written informed consent was obtained prior to data collection.

All participants for this study were screened for pre-existing conditions that would affect their upper and lower extremity performance (e.g. back surgery/injury, joint surgery/injury, medication, etc.). Any conflicting condition excluded these individuals from participation. Following screening participants completed a single session, with breaks permitted upon request.

Questionnaire

The questionnaire included inquiries about education history, mental and physical health history, and the post-concussion symptoms scale (SCAT-2)^{40, 46}. Concussion history was evaluated in two ways^{12, 43}. First, participants were asked if they had ever sustained a blow to the head or body resulting in a concussion that was diagnosed by a licensed medical professional (i.e., physician, athletic trainer, emergency medical technician, nurse). If participants answered “no” to this question they were then provided with a list of common concussion symptoms used in clinical diagnostic interviews⁴⁷ and asked if any occurred following a blow to the head. To be included in a concussion history group, the participant must have responded ‘yes’ to one or both of the aforementioned concussion history

questions. No attempt was made to grade injury severity due to the known inconsistency of grading scales¹. Participants who indicated 'no' to both concussion history questions were assigned to the control group.

Computerized Cognitive Assessment Tool (CCAT)

Each participant completed the AXON (currently CogState) CCAT. The AXON CCAT consists of four test modules: detection (simple reaction time), identification (choice reaction time), one card learning (working memory), and one back speed/accuracy (attention and working memory). The test is based on rapidly tapping a computer key in response to images of playing cards displayed on the computer monitor. Greater detail of the AXON CCAT test has been previously reported^{17, 22, 23}. This test has been widely used in the sport concussion literature^{17, 22, 38} with moderate to high reliability^{17, 22} and sensitivity³⁸. The AXON CCAT yields five standardized output scores: processing speed, attention, learning, working memory speed, and working memory accuracy, with higher output scores indicating better performance.

Discrete Temporal Auditory Task

A multitude of metronomic tasks have been widely used in various research fields and populations^{26, 30, 31}. To evaluate implicit and explicit timing variability, a discrete temporal auditory task was developed and administered using LabView 2011 software (National Instruments, Austin, Texas, USA). The discrete temporal task was completed with both the dominant hand and foot (without shoe) with the participant seated. For the foot condition, the rubber bladder was placed beneath a custom foot pedal (Figure 1, bottom). The same rubber bladder was placed in the participant's dominant hand for the hand condition. A rubber bladder was chosen to allow for the same device and similar functional mechanism (squeezing/compressing) to be used to complete the task with both the hand and foot.

For both conditions, a pacing tone was played over speakers at either a 1Hertz (Hz; one tone/second) or 0.5Hz (one tone/two seconds) pace for a total of 60s. Participants were instructed to react to the designated pace by squeezing/depressing the air bladder as soon as the tone was presented. In six trials the pace was present for the full duration of the one-minute trial. For an additional six trials, the pacing mechanism ceased after the first 10s, requiring the subject to continue the pace for the last 50s. Each participant completed a total of 12 trials with the hand and 12 trials with the foot. The paced trials assessed the sensorimotor control associated with explicit synchronization, while the un-paced trials assessed the sensorimotor control of implicit timing. Lead/lag time for paced conditions was measured as the amount of time between the stimulus and the participant's response. Lead/lag time for un-paced conditions was measured as the time between responses minus the time that should have elapsed according to the defined pace. Variance was calculated for each participant under each condition using the following formula: the sum of the absolute difference of each subject's response from the subject's mean response, multiplied by one over the total number of observations, minus one.

Force Controlled Continuous Tracking (CTT)

During the CTT participants were seated in front of a computer monitor and instructed to track a target as it moved up and down the screen according to a random sine-cosine waveform. This technique has previously been used successfully in healthy and diseased populations^{7, 32, 57, 58}. The target appeared as a red dot and the participant-controlled cursor appeared as a white circle (Figure 1, top). Participants controlled the position of the white circle by applying graded force to an air bladder connected to a pressure sensor (Omega.com; model PX209–015G5V; range of 0–15 psi with a 5V output) by either depressing the pedal device with their foot or squeezing the rubber bulb with their hand. Again, the rubber bladder allowed for the same device and similar functional mechanism (squeezing/compressing) to be used to complete the task with both the hand and foot. Sampling of the pressure and visual display updating occurred at 40Hz using custom LabView 2011 software. Participants completed a total of three 30s epochs using their dominant hand and three 30s epochs using their dominant foot.

For hand tracking, prior to starting the three 30s epochs, participants were asked to squeeze as hard as possible on the rubber bulb in the dominant hand for 15s. The vertical displacement of the target during the subsequent tracking epochs was scaled to a force range between 25 and 75% of their average maximum voluntary force over this 15s epoch.

For the foot condition, the rubber bladder was placed beneath a custom foot pedal (Figure 1, bottom). Again, participants completed a 15s epoch to determine maximum force. The vertical displacement of the target during the subsequent tracking epochs was scaled to a force range between 25 and 75% of their average maximum voluntary force of the foot over this 15s epoch.

For both hand and foot tracking root mean square error (RMSE) values were derived as the average of the difference waveform, which was derived by subtracting the instantaneous position of the target from the participant's location. RMSE for each thirty-second epoch was averaged within each participants' trial per limb condition.

Statistical Analysis

Means and standard deviations were calculated for the questionnaire, AXON CCAT output scores (e.g. processing speed, attention, etc.), lead/lag time variability for the discrete timing task, and RMSE values for the CTT. Independent sample t-tests were used to compare demographic variables between the concussion history groups within age and each task-specific outcome variable between concussion history groups, independent of age. Bonferroni corrections were applied to account for multiple comparisons. Cohen's d effect sizes were calculated to assess the between concussion history groups' performance¹⁵. Each outcome variable was then analyzed using linear regression, with age as a continuous variable: first, using a regression model with age as the sole independent variable (model-1), and then using a multiple regression model that included age, concussion history group, and an interaction term (concussion history $\times$ age) (model-2). Adjusted R-squared values (Adj R²) were reported as a correction for multiple predictors, as indicated. Pearson's correlations were also calculated for each outcome variable and the regression model-2

predictors. The α -level was set *a priori* at $p = 0.05$. Statistical analysis was completed using SPSS software version 21.

Results

Questionnaire:

There were no significant differences between concussion history groups, within age group, or across the entire study population, for any of the demographic variables (Table 1).

AXON CCAT:

There were no significant differences between the control and concussion history groups for any of the AXON output scores (Table 2).

The model-1 regression analyses identified no significant age effects for processing speed, learning, or working memory accuracy output scores. Both attention ($F = 4.59$, $p = 0.04$, $R^2 = 0.06$) and working memory speed ($F = 13.45$, $p < 0.01$, $R^2 = 0.15$) model-1 regression equations identified statistically significant age effects (Beta = -0.24 , $t = -2.14$, $p = 0.04$ for attention; Beta = -0.39 , $t = -3.67$, $p < 0.01$ for working memory accuracy).

Only working memory speed model-2 regression equation reached statistical significance (Table 3; $F = 5.21$, $p < 0.01$, Adj $R^2 = 0.14$). However, none of the individual Beta coefficients were significant. Pearson correlation (Table 4) analyses indicated statistically significant, but only low to medium correlations for Age and the Interaction predictors.

Discrete Auditory Timing:

There were no significant differences between the control and concussion history groups for the discrete auditory timing task (Table 2).

Three model-1 regression analyses were significant for the hand and foot conditions. For hand trials, the 1Hz un-paced ($F = 13.76$, $p < 0.01$, $R^2 = 0.16$) and 0.5Hz un-paced ($F = 6.37$, $p = 0.01$, $R^2 = 0.08$) conditions identified significant age effects (Beta = 0.39 , $t = 3.71$, $p < 0.01$ for 1Hz un-paced; Beta = 0.28 , $t = 2.52$, $p = 0.01$ for 0.5Hz un-paced). For the foot trials, only the 0.5Hz paced condition yielded a significant age effect ($F = 4.21$, $p = 0.04$, $R^2 = 0.05$; Beta = 0.23 , $t = 2.05$, $p = 0.04$).

The only statistically significant model-2 regression analysis was for the hand 1Hz un-paced condition ($F = 4.65$, $p < 0.01$, Adj $R^2 = 0.16$). However, none of the individual Beta coefficients for age, concussion history, or the interaction between the two limb conditions reached significance (Table 3). Pearson correlation (Table 4) analyses indicated statistically significant, but only low to medium correlations for Age and the Interaction predictors.

CTT:

There were no significant differences between the control and concussion history groups for either the foot or hand conditions (Table 2).

Both the model-1 regression analyses for the hand ($F = 27.79$, $p < 0.01$, $R^2 = 0.27$) and foot ($F = 32.14$, $p < 0.01$, $R^2 = 0.29$) identified significant age effects ($Beta = 0.52$, $t = 5.27$, $p < 0.01$ for the hand condition; $Beta = 0.55$, $t = 5.67$, $p < 0.01$ for the foot condition).

Further, the model-2 regression analyses were statistically significant for both the hand ($F = 9.33$, $p < 0.01$, $Adj R^2 = 0.25$) and the foot ($F = 10.82$, $p < 0.01$, $Adj R^2 = 0.28$) conditions (Table 3). However, the only statistically significant Beta coefficient was for age during the foot condition ($Beta = 0.79$, $t = 2.69$, $p < 0.01$). None of the other individual Beta coefficients reached significance under either limb condition. Pearson correlation (Table 4) analyses indicated statistically significant, but only low to medium correlations for Age and the Interaction predictors.

Exploratory regression analyses assessing number of previous concussions (as a continuous variable) as a predictor of task performance yielded no significant correlations between number of previous concussions and task outcome variables and no significant Betas for number of previous concussions. The sample size herein is insufficiently large to evaluate task outcome variables by number of concussion groups (e.g. 0, 1–2, 3+)²⁹.

Discussion

The purpose of this investigation was to determine if sustaining an adolescent concussion negatively affects cognitive and motor performance across age. These results failed to identify any observable differences between those with and without an adolescent concussion history, as measured by clinically based neurocognitive assessment scores or upper and lower extremity motor performance measures. Age was a significant factor for predicting performance in this study, with a trend of decreasing performance with increasing age. This is not surprising given that age-related effects on cognitive and motor performances are well established in the literature^{35, 45}. If a history of concussion during adolescence does have any adverse effects on cognitive or motor performance, these effects may have limited functional significance or be restricted to individuals demonstrating specific traits across the lifespan not quantified here.

Discrepancies in both neurocognitive and motor performance have previously been observed in asymptomatic young and middle-aged adults with a concussion history^{12, 14, 19–21, 43, 54, 56}. In these investigations, subtle differences were identified from one to six years following injury^{12, 14, 19–21, 43, 54, 56}. While statistically significant, the clinical relevance of these small cognitive and motor performance differences remains unclear with respect to their effect on an individual's daily function. This study extends the age range of individuals assessed for deficits in cognitive and motor function following adolescent concussion(s). To the authors' knowledge, this investigation is the first to assess motor performance of the upper extremity in an adolescent concussion history population.

Post-concussion symptom scale scores (Table 1) yielded no statistical significance between the adolescent concussion history and control groups. These findings provide additional support to the absence of long-term effects of concussion history on symptom reporting^{12, 33}. Further, most (80–90%) concussed athletes return to pre-injury symptom

levels within 7–10 days of injury, with symptom recovery in as few as four days in high school athletes^{39, 47}. More prolonged reporting of concussion related symptoms is rare and may suggest the presence of other clinical maladies, such as post-concussion syndrome, depression, or other psychological factors⁵¹.

Previous studies have identified an effect of concussion history on electrophysiological measures associated with attention and decision making processes, observed between three and thirty years following concussion recovery^{12, 19, 20, 54}. Though electrophysiological assessment was not included in this study, the absence of concussion group differences on the Axon CCAT suggests that the previously observed electrophysiological differences may not be associated with overt clinical changes in neurocognitive performance. That these studies have failed to identify significant differences in neurocognitive performance between the concussion history and control groups in parallel with the observed electrophysiological differences^{12, 19, 54}, may indicate that the previously concussed individuals are adopting compensatory mechanisms capable of overcoming any performance decline that would otherwise have been associated with the observed electrophysiological alterations.

Further, our neurocognitive assessment findings are consistent with other previous studies that also failed to identify significant long-term neurocognitive differences in previously concussed college athletes^{11, 16, 21, 33}. This is also consistent with the finding that most acutely concussed individuals return to their baseline performance on cognitive measures within seven to ten days post-concussion⁴⁷. Given that CCATs are designed to assist with the clinical diagnosis and management of acute concussion, a potential alternative explanation for these null findings is that CCATs are simply insensitive to the type or magnitude of long-term cognitive impairment attributable to remote concussion. Future investigations should implement more sensitive measures of functional cognitive assessment. While the AXON CCAT and electrophysiological studies do not measure the same constructs, the results herein do not support the presence of “whole system” concussion effects on cognitive performance with age.

This investigation is the first to assess a CTT or a discrete temporal auditory task in an adolescent concussion history population. Discrete timing has previously been implemented to differentiate those with and without Alzheimer’s disease (AD). Considering the pathological and clinical similarities between CTE and AD, the CTT and a discrete temporal auditory task are suggested as a potential assessment tool in the aging post-concussion population^{3, 4, 24, 48, 49}. Older, healthy adults were not significantly more variable in a discrete timing task than younger adults, yet were significantly less variable than older adults in the early stages of AD³. We found no differences between concussion history and control group (Table 2), regardless of age, or any significant concussion predictors (Table 3) for discrete timing task variability. This would suggest that adolescent concussion history does not have a significant effect on implicit or explicit timing variability, at least not to the same degree of effect that early stage AD does.

There is limited evidence for an effect of AD on performance during a similarly complex CTT, although the magnitude of differences in performance on this rotor pursuit task between the AD and control groups was small⁵⁷. In the present study there were no

significant differences between the concussion history and control groups for the CTT (Table 2), nor was there a significant main effect for concussion (Table 3) in model 2 regression analyses. Previous investigations have observed age-related differences between healthy young and older adults using alternative CTTs to assess variability and performance^{34, 52}. Similarly, in the present study age appears to be the strongest predictor of performance on the CTT.

A potential explanation for the lack of concussion history effects could be that the discrete temporal auditory task and CTT, as implemented in the current methodology, are not sensitive enough to distinguish the subtle performance differences between the concussion history and control groups, should they exist. The current methodology is a motor performance assessment, which may present as unaffected by concussion due to the adoption of compensatory mechanisms by the previously concussed that mask underlying deficits related to more complex processing. If this is the case, the subtlety of the adolescent concussion history effects on cognitive and motor performance are unlikely to significantly influence activities of daily living in a clinically meaningful way, at least without taking into account other possible factors (e.g. genetics, recreational drug use, or alcohol). The ability to compensate to achieve task success has been observed in more neurologically impaired populations^{8, 9}. How a compensatory mechanism is selected or implemented by the previously concussed is beyond the scope of this investigation, but should be investigated moving forward, whereby multiple session exposure are included to assess implicit/explicit learning, which has been shown to be impaired in other pathological conditions^{7, 57}.

Another possible reason for lack of adolescent concussion history effects could be that the neurological underpinnings between AD and adolescent concussion history are not the equivalent. Any variability in neurological dysfunction could result in differing performance on similar tasks, when compared to a matched control sample. While literature exists about the possible physiological underpinnings of both concussion history^{24, 48, 49} and AD⁵, additional investigations need to be completed to gain a stronger certainty of the physiological underpinnings, particularly for concussion history.

Study Limitations:

The most prominent limitation of this study was limited power to detect significant differences due to the imbalanced age and concussion history groups and the relatively small sample sizes within each group, particularly in the older age groups. Because of the uneven group sizes, age was analyzed as a continuous variable using regression analyses rather than as a categorical variable using analysis of variance. Another limitation is that this study only investigated motor performance at one time point. It is possible that sub-clinical deficits that are not evident during motor performance may become accentuated during skill learning and/or motor adaptation⁵⁰. Future examination of the adolescent concussion history population should implement these methodological aspects of the CTT to provide further insight for the adolescent concussion history literature. Additionally, all concussion history information was based on self-report, though this is not uncommon in concussion literature^{11, 42, 43}.

Conclusion

The results presented here are the first to evaluate cognitive and motor performance across the lifespan among those sustaining an adolescent concussion(s) without subsequent concussion(s) during adulthood. Previous investigations have reported subtle differences in cognitive and motor performance between concussion history and control groups^{14, 18, 43, 56}. The findings from this investigation however, extend this prior work by demonstrating a limited relationship between adolescent concussion history and cognition or motor performance across a broader age spectrum. As expected, age had a consistent adverse effect on cognitive and motor performance. However, adolescent concussion history had no consistent effect on cognitive or motor performance, in the population assessed herein. In light of these findings, caution is necessary when relating late-life risks documented in former professional athletes to those athletes whose sport participation and concussion histories were limited to high school level sports. Attempting to compare the potential effects of a professional athlete's career's worth of repeated head impacts and concussions to those of a high school athlete's career is highly misguided, given the discrepancy in head impact exposure between the two cohorts. Importantly, this study offers a generally positive, though incomplete, outlook for those athletes who compete at the high school level of play and represent the largest subset of the concussion history population. Future research should expand upon this work, including longitudinally tracking of former high school athletes prospectively and accounting for the number of previous concussions sustained to provide a more complete assessment understanding of the effect of an adolescent concussion history on cognitive and motor performance across the lifespan.

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List of Abbreviations:

Hz	Hertz
Adj R²	Adjusted R-squared
s	second

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Current understanding:

Limited literature exists about the cognitive and motor performance of individuals who sustained an adolescent concussion, with no subsequent concussions after high school. This is particularly true for populations older than undergraduate students.

What the current study adds:

The results herein add the older, adolescent concussion history populations who have been largely over looked, as well as two motor control assessments that have not been used in the long-term concussion literature. Ultimately, this manuscript begins to fill the adolescent concussion history gap in the literature.

Figure 1:
Continuous tracking task. LabView based visual display (top) and foot device to evaluate force control. Participant's heel touches back lip (bottom). The rubber bulb under the device was held to evaluate hand control (not shown).

Table 1.

Demographic Information

	20 Year Olds		40 Year Olds		60 Year Olds	
	Control	Concussed	Control	Concussed	Control	Concussed
n	24	19	14	4	15	7
Sex (% male)	46	47	50	75	47	86
Age (y)	21.6(2.2)	20.3(1.6)	44.9(3.3)	47.3(3.5)	63.6(3.5)	62.4(3.7)
Height (cm)	172.4(9.1)	173.2(9.7)	170.7(11.8)	181.0(10.2)	170.0(10.2)	174.5(6.7)
Weight (kg)	68.2(12.3)	68.7(14.8)	79.8(11.5)	94.7(20.1)	78.0(14.3)	77.2(8.4)
Previous # Concussions	.	1.6(0.7)	.	2.8(1.7)	.	2.3(1.8)
Time Since (y)	.	5.6(3.2)	.	23.7(13.2)	.	48.4(5.0)
Symptoms	2.3(4.8)	5.5(6.5)	1.9(2.3)	1.0(2.0)	1.5(3.2)	2.1(4.4)
Total Years of Education	14.9(1.5)	14.0(1.5)	16.3(1.7)	17.3(1.0)	16.8(2.6)	16.8(1.3)

Mean(standard deviation). No significant concussion group differences within age (p 's > 0.05).

TABLE 2:

Concussion History Group Means (standard deviation) for each outcome variable

			Control (n=53)	Concussion History (n=30)	Cohen's d
AXON CCAT		Processing Speed	97.72(4.88)	96.55(7.19)	0.20
		Attention	102.98(4.17)	103.13(4.74)	0.03
		Learning	103.98(7.65)	104.33(5.70)	0.05
		Working Memory Speed	99.84(5.53)	98.88(6.83)	0.16
		Working Memory Accuracy	105.48(9.10)	103.05(5.96)	0.30
Discrete Auditory Task	Hand	1Hz Paced	0.01(0.01)	0.02(0.02)	0.38
		.5Hz Paced	0.02(0.01)	0.02(0.01)	0.06
		1Hz Un-Paced	43.35(20.94)	44.34(21.70)	0.05
		.5Hz Un-Paced	87.64(42.23)	93.23(41.92)	0.13
	Foot	1Hz Paced	0.03(0.03)	0.02(0.01)	0.27
		.5Hz Paced	0.02(0.02)	0.03(0.02)	0.07
		1Hz Un-Paced	49.97(14.78)	52.28(7.73)	0.18
		.5Hz Un-Paced	103.67(24.86)	95.85(34.64)	0.28
Continuous Tracking Task	Hand		8.24(1.85)	7.68(2.07)	0.30
	Foot		8.59(2.04)	8.27(1.90)	0.16

Mean(standard deviation), all p 's > 0.05. Paced indicates the pacing tone persisted across the full trial. "Un-paced" indicates the pacing tone dropped out after the first 10 seconds of the trial. AXON CCAT: higher output scores are better. Continuous Tracking Task: RMSE scores, lower score is better.

TABLE 3:

Regression Model 2 Beta Values

		Predicted in Model	Adjusted R ²	Age Beta	Concussion Beta	Interaction Beta
AXON CCAT		Processing Speed	−0.01	−0.43	−0.36	0.44
		Attention	0.02	−0.17	0.03	−0.09
		Learning	−0.02	0.36	0.18	−0.27
		Working Memory Speed	0.14	−0.61	−0.28	0.23
		Working Memory Accuracy [*]	0.00	−0.40	−0.41	0.44
Discrete Auditory Task	Hand	1Hz Paced	0.05	−0.27	−0.11	0.53
		.5Hz Paced	−0.01	−0.05	−0.15	0.24
		1Hz Un-Paced [*]	0.13	0.45	0.11	−0.06
		.5Hz Un-Paced	0.05	0.25	0.07	0.06
	Foot	1Hz Paced	0.05	0.67	0.22	−0.56
		.5Hz Paced	0.02	0.12	−0.02	0.15
		1Hz Un-Paced	−0.02	−0.07	−0.01	0.18
		.5Hz Un-Paced	0.03	−0.26	−0.41	0.52
Continuous Tracking Task		Hand ^{**}	0.25	0.43	−0.13	0.09
		Foot ^{**}	0.28	0.79 [*]	0.16	−0.30

Values represent regression model 2 analyses with standardized Beta values.

^{*} Indicates $p < 0.05$,

^{**} indicates $p < 0.001$.

If asterisk is in the model column that indicates the model was significant. If asterisk is in a Beta column, indicates that factor is significant.

TABLE 4:

Pearson Correlation

			Age	Concussion	Interaction
AXON CCAT		Processing Speed	-0.04	-0.09	-0.05
		Attention	-0.24 *	0.01	-0.20 *
		Learning	0.12	0.01	0.08
		Working Memory Speed	-0.39 **	-0.08	-0.35 **
		Working Memory Accuracy	0.00	-0.15	-0.04
Discrete Auditory Task	Hand	1Hz Paced	0.15	0.17	0.27 **
		.5Hz Paced	0.15	-0.03	0.13
		1Hz Un-Paced	0.39 **	0.02	0.34 **
		.5Hz Un-Paced	0.28 **	0.06	0.27 **
	Foot	1Hz Paced	0.21 *	-0.13	0.05
		.5Hz Paced	0.23 *	0.03	0.23 *
		1Hz Un-Paced	0.07	0.09	0.13
		.5Hz Un-Paced	0.19	-0.13	0.13
Continuous Tracking Task		Hand	0.52 **	-0.14	0.36 **
		Foot	0.55 **	-0.08	0.39 **

* Indicates $p < 0.05$,

** indicates $p < 0.01$.