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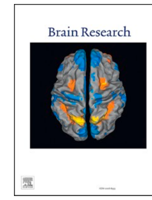

Evidence of residual cognitive deficits in young adults with a concussion history from adolescence

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A R T I C L E I N F O

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A B S T R A C T

The present study investigated executive function and sustained attention of non-athlete, young adults (ages 18–23) with a history of concussion beyond ten months post incident. Cognitive functioning was examined in 24 non-athletic, college students with a concussion history (mean age 21 yrs.; mean time and range post-injury: 4 years, 10–90 months) and 24 non-athletic controls with no history (NH) of concussion. Computerized versions of two cognitive assessment techniques were utilized to examine executive functioning (Stroop) and sustained attention capacity (D2). Primary dependent variables were response time, error score, and sustained attention score. Relationships between dependent variables and concussion metrics were also analyzed. ANOVA's revealed a significantly higher error rate in concussion history (CH) participants when performing the Stroop task ($p < 0.05$), including a trend for greater errors in the incongruent task condition ($p < 0.05$). Group measures did not differ in the sustained attention test (all $p > 0.05$). Nevertheless, there was a significant relationship between D2 error rate and time since concussion ($p < 0.01$), showing that D2 error rate was greater for participants with more time since concussion sustainment. Our findings indicate the potential for prolonged cognitive dysfunction linked to decision-making, but not to processing speed, in young adult non-athletes with a CH averaging four years post-injury. These findings may provide evidence of residual cognitive deficits in young adults with a concussion history over time.

1. Introduction

Concussions are a mild form of Traumatic Brain Injury (mTBI) associated with temporary impairment of motor skills and diminished cognitive functioning (McCrory et al., 2017). With nearly three million incidents of mTBI occurring annually in the United States, most concussion research has examined post-impact behavioural cognitive functioning with an emphasis on immediate effects (e.g. youth or college-aged athletes) or more long-term implications (e.g. elderly individuals at risk for earlier onset of Alzheimer's disease and dementia) (Alsalaheen et al., 2017; Manley et al., 2017). Considerably less research, however, has examined possible prolonged cognitive impairments in young adult non-athletes who experienced a concussion in adolescence. While numerous studies have documented impairments in young adults up to eight months post-injury, research beyond this time frame is limited. Notably, there is increasing evidence that the effects of concussions can persist well beyond the acute stage of injury and the initial first few months post-impact, potentially progressing for years (Broglio et al., 2011). This suggests the need for a more basic understanding of cognitive impairments beyond year one, and well before the potential onset of dementia and other elderly-related problems.

Studies have reported cognitive impairments in young adult athletes relatively soon after head injury (two days to two months post-concussion), when using assessments such as executive function tests linked to response inhibition or to attention level (Ellemberg et al., 2007; Howell et al., 2013; van Donkelaar et al., 2005). However, these findings are associated with rather acute concussion stages and do not provide information about long-term cognitive impairments. Nevertheless, they do provide evidence that response inhibition and attention tasks can be sensitive to neurological changes linked to concussive head injuries in young athletes. For example, prolonged deficits in brain activity (N2 and P2b amplitude during EEG measurements) were found in young adult athletes when testing was completed around three years post-concussion, however, participant functional outcomes remained intact (i.e., cognitive control and attention measured by the ImPACT and Flanker test) (Broglio et al., 2009; Pontifex et al., 2009). These findings suggest persistent impairments in the neuroelectric system, even in the

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absence of behavioural cognitive declines. These neuroelectric impairments could potentially be a result of compensatory mechanisms that avoided possible functional deficits from emerging.

Other studies have investigated functional outcomes of concussion history participants by examining the effects head trauma may pose on sustained attention levels. Sustained attention, the ability to maintain concentration through the duration of a task, is a crucial aspect of adaptive functioning, and diminished levels can have significant impacts on decision making and performance outcome (Manly & Robertson, 1997; McAvinue et al., 2012). Studies have found deficits in sustained attention levels of children with a history of mTBI, determining that children injured earlier in childhood perform worse on sustained attention tasks, regardless of concussion severity (Ewing-Cobbs et al., 1998; Kramer et al., 2008). These studies have shown that children with a concussion history may be at greater risk for long-term impairments in cognitive processing speed and accuracy (Kramer et al., 2008). However, sustained attention research beyond this age range is limited. To the best of our knowledge, the effects concussions pose on sustained attention have not been investigated in young adult individuals with a concussion history from adolescence.

In addition, while many studies have investigated cognitive functioning in adolescent participants with a history of concussion, most of the research emphasis has been on athletes. However, daily environmental exposures present athletes with a greater risk for sport-related head injuries, and if undiagnosed, could potentially undermine study results. Moreover, athletes in collision and contact sports are regularly exposed to sub-concussive blows to the brain, which have been proven to impact cognition (Di Virgilio et al., 2016; McNabb et al., 2020; Moore et al., 2017). By testing non-athlete college students, researchers could diminish the likelihood of frequent sub-concussive blows to the head, thereby providing a more accurate depiction of post concussive dynamics. This approach could offer further evidence for the notion that potential cognitive or functional impairments found in young adulthood might persist for several years post-concussion, even in non-athletes.

To the best of our knowledge, few studies have investigated the effects that concussions from adolescence play on brain function in non-athlete college students. Specifically, one study tested young adult participants averaging four years post-injury, however, their findings drastically contrast with the other studies mentioned in the previous paragraphs (Martini et al., 2017). Martini and colleagues did not find evidence of cognitive impairments when using a computerized cognitive assessment tool (Axon CCAT), which tested simple and choice reaction time, working memory, as well as attention (Martini et al., 2017). Nevertheless, they acknowledged that their cognitive tests might not have been sensitive enough to assess prolonged cognitive behavioural dysfunctions post-injury, suggesting future research should shed further light on this issue (Martini et al., 2017). In support of this notion, one of their earlier studies found prolonged changes in gait pattern in young adults with a concussion history six years post-injury during a dual mobility and cognitive test (Martini et al., 2011). This finding provides tentative evidence that long-lasting impairments based on high-order functions can occur.

By using executive function and sustained attention tests that have been proven sensitive to cognitive impairments, the present study applies previous work to an under-researched population (Dalecki et al., 2012; Ellemberg et al., 2007; Howell et al., 2013). Specifically, we examine potential intermediate-term cognitive impairments in non-athletic, young adults with a history of a mTBI from adolescence. Based on findings reported in previous studies, we hypothesize that participants with a concussion history might process cognitive information less efficiently than participants without a history of concussion (s).

2. Results

ANOVA outcomes and descriptive statistics for each cognitive test and the SCAT 5 assessment are summarized in Tables 2 and 3. Analyses using sex, number of concussions, and sport classification (see Table 1) as a main effect yielded no significant differences for all dependent variables (all $p > 0.05$). Thus, data was merged across sex, number of concussions, and sport classification.

Young adult participants with a concussion history processed cognitive information less efficiently when compared to participants with no history of concussion. Concussion history participants experienced greater Stroop error rate than no history control participants, as well as lower immediate memory and concentration scores. Participants with a concussion history also experienced greater symptom severity. Further details are presented in the sections below.

2.1. *Stroop task performance in both groups*

For the Stroop task, ANOVA yielded a significant main effect of group for error rate, revealing a higher error rate in concussion history participants ($p = 0.029$), and a trend for a group × condition interaction ($p = 0.076$). Further investigation through pairwise comparison acknowledged a higher error rate in the incongruent task condition for concussion history participants compared with no history controls ($p < 0.05$), but only a trend in the congruent task condition ($p = 0.074$) (Fig. 1b). For response time, there was no significant main effect of group and no group × condition interaction (all $p > 0.05$) (Fig. 1a). There was also no significant group effect for Stroop interference, for either error rate or response time (all $p > 0.05$) (Fig. 1c, 1d).

2.2. *D2 task performance*

For the D2 task, ANOVA revealed no significant main effects of group for sustained attention score, overall response time, and error rate (all $p > 0.05$). The results suggest that dependent variables of the sustained attention test did not differ between the concussion history and no history groups (Fig. 2a–c).

2.3. *SCAT 5 results*

For the SCAT 5 symptom and cognitive assessment, ANOVA revealed a significant main effect of group for symptom severity, immediate memory, and concentration (all $p < 0.05$). Concussion history participants experienced a significantly higher symptom severity, and a significantly lower immediate memory and concentration score than the no history control group (Tables 1 and 2). There were no significant main effects of group for number of symptoms, orientation, and delayed recall (all $p > 0.05$).

2.4. *Relationship between cognitive performance, symptoms, and concussion history metrics*

Correlation analysis yielded no significant relation between Stroop or SCAT 5 performance variables with time since first concussion (months), time since last concussion (months), and number of concussions. However, it did reveal a significant relationship between D2 performance variables and time since first concussion (months) and time since last concussion (months). The number of D2 errors was positively correlated with time since last concussion ($R = 0.732$, $p < 0.001$) (Fig. 2d), suggesting that the D2 error rate was greater in CH participants with a longer amount of time since injury. We found the same pattern of findings between the D2 error rate and the time since first concussion ($R = 0.732$, $p < 0.001$) (Fig. 2e). Finally, we found a significant positive correlation between the SCAT 5 symptom severity and the number of concussions ($R = 0.489$, $p < 0.05$), revealing that symptom severity was higher for participants with more concussions.

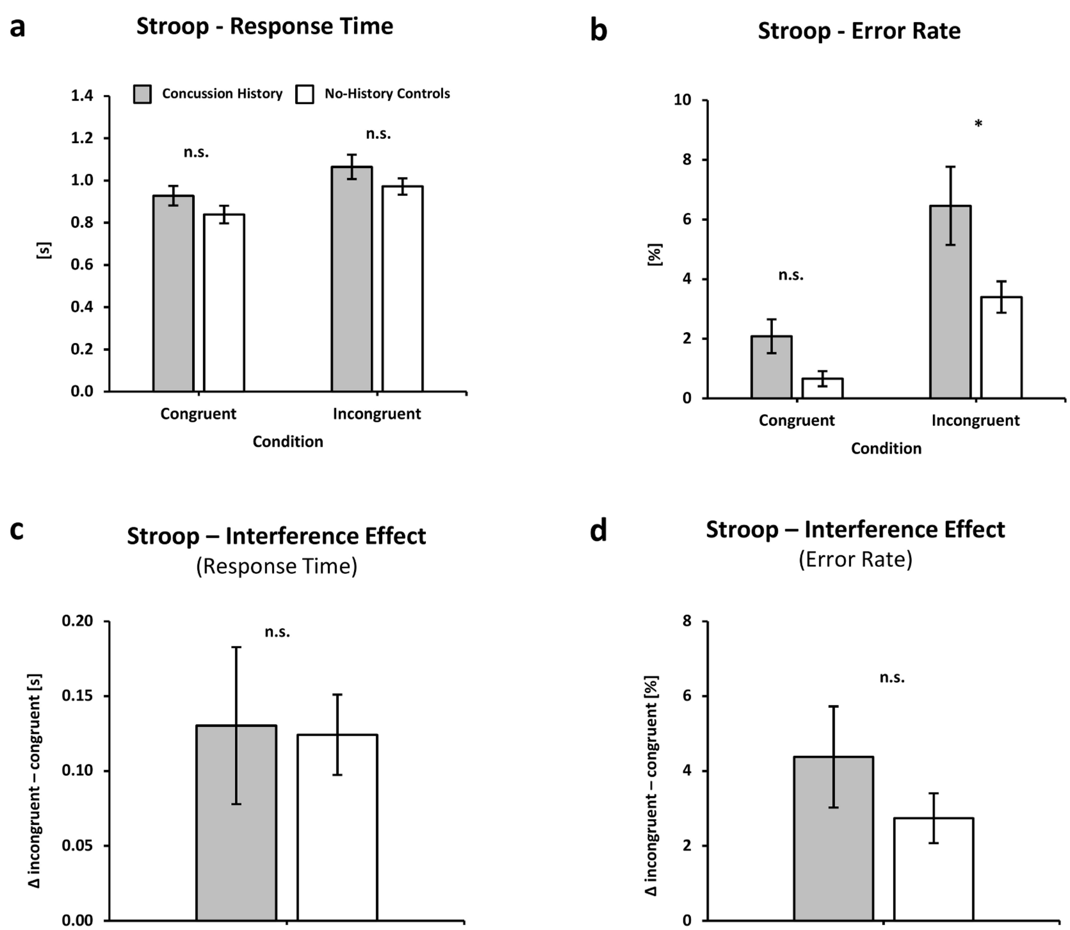

Fig. 1. Summarizes the mean results of the Stroop test for **a)** response time, **b)** error rate, and interference effect for **c)** response time and **d)** error rate for the CH and NH groups. Note a higher error rate in the CH group with a trend for a more pronounced effect in the incongruent task condition. * = $p < 0.05$, n.s. = non significant. Error bars represent the standard error of the mean.

3. Discussion

The present study investigated executive function and sustained attention in young adult, non-athlete college students with a concussion history from adolescence. Results indicated that concussion history (CH) participants experienced prolonged executive function deficits when tested averaging four years post-impact, as well as a trend for a more pronounced effect in tasks linked to response inhibition and high-order cognitive control. Sustained attention was similar between both study groups; however, error rate was greater in individuals with more time since injury within the CH group.

Young adults with a history of concussion were found to process cognitive information less efficiently than participants with no history (NH) of concussion. Specifically, CH participants experienced a significantly higher error rate in the Stroop color-word task, indicating less efficient cognitive control (Goghari and MacDonald, 2009; Herd et al., 2006). Our findings may support evidence that potential long-term damage from concussions could result in the dysregulation of cognitive control networks in the brain, as shown in studies with other age groups (Churchill et al., 2017). This dysregulation may be responsible or related to the behavioural outcome changes with high-order cognitive control rather than problems with processing speed itself. Indeed, inhibitory control, such as response inhibition during a Stroop task, is largely driven and distributed by fronto-parietal networks in the brain (Goghari and MacDonald, 2009; Grandjean et al., 2012; Herd et al., 2006). During response inhibition tasks, brain-imaging studies indicated fronto-parietal network dysfunction as a cause of lower high-order cognitive control in various populations (Barrós-Loscertales et al., 2011; Grandjean et al., 2012; Roberts & Garavan, 2010). Moreover, studies using brain-imaging showed structural changes in white matter tracts within the fronto-parietal networks of retired football athletes with a CH from young adulthood (Tremblay et al., 2014), as well as in adolescent's one-month post-concussion (Krivitzky et al., 2011).

The current findings support previous work that utilized similar assessments to our study, and reported decrements of executive control but not of attention in adolescents up to two months post-concussion (Howell et al., 2013). Our study also expands on previous work that reported cognitive dysfunctions in participants with a concussion history, such as diminished response accuracy in a Flanker test (Pontifex et al., 2009). Similarly, through utilizing a stroop task, Ellemberg and colleagues determined that processing speed of young adult female college soccer players declined when testing was completed less than one-year post-concussion, however their decision-making skills remained intact (Ellemberg et al., 2007). In contrast, our results differ with one of the few other studies that investigated cognition of young adults several years after concussion sustainment. Notably, Martini and colleagues did not find diminished cognitive functions in young adults averaging six years post-injury (Martini et al., 2017). While these results are in contrast with other studies that found deficits in adolescents, Martini and colleagues suggest this may be contributed to outside studies testing participants sooner post-injury (Martini et al., 2017). However, they acknowledge that task differences and task sensitivity from lingering effects of brain dysfunction could be a potential reason for this discrepancy as well (Martini et al., 2017).

The latter assumption would be in agreement with our present study findings. Potentially, the Stroop color-word task may exhibit a greater

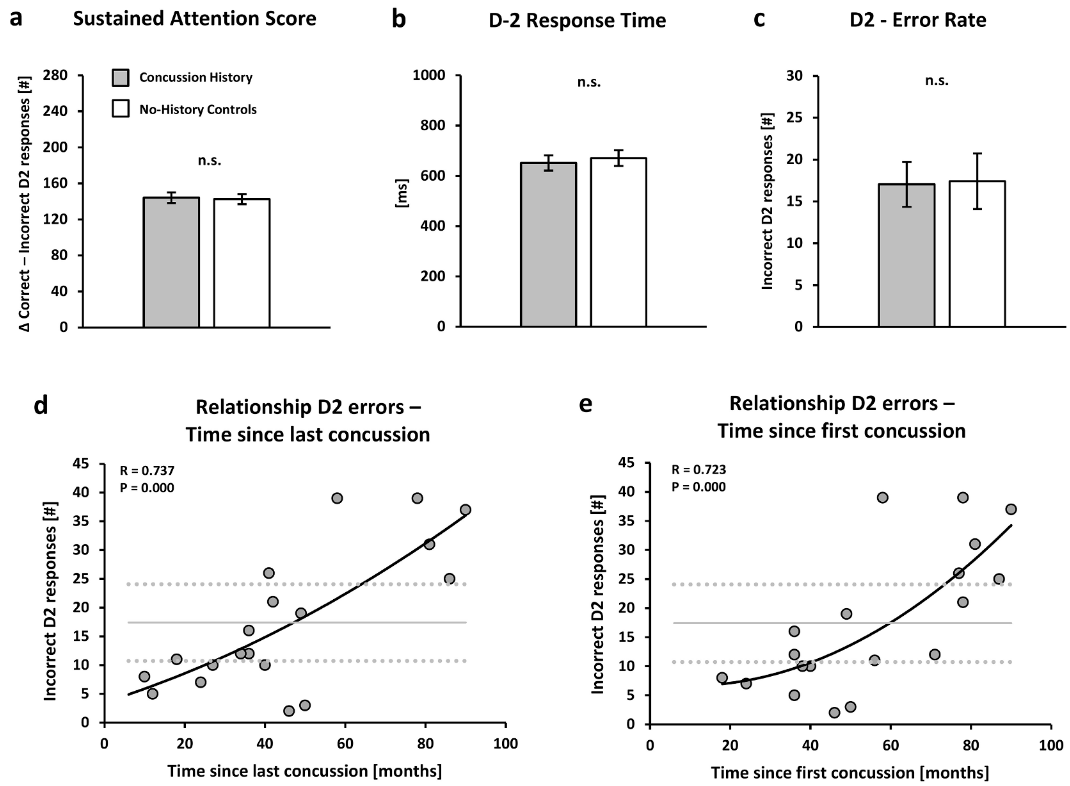

Fig. 2. Summarizes the mean results of the D2 test for **a)** sustained attention score, **b)** response time, **c)** error rate for the CH and NH groups, **d)** the relation between D2 errors and time since last concussion (months), and **e)** the relation between D2 errors and time since first concussion (months) for the CH group. Graph **d)** and **e)** also shows the mean D2 error values for the control participants with no history of concussion (i.e., the baseline performance of healthy participants), plotted as grey solid line along the x-axis, and baseline 95% CI represented by both grey dashed lines along the x-axis. Note an intact sustained attention, response time, and error rate, but an increasing D2 error rate with increasing time since last and first concussion within the CH group. n.s. = non significant. Error bars represent the standard error of the mean.

Table 1
Participant demographic information of those who were included into data analysis. Abbreviations: Conc. = Concussion; hist. = history; Contr. = Controls; # = number; n/a = not available.

	Conc. hist. (n = 20)	No-hist. contr. (n = 23)
Sex, F/M	11/9 (55% F)	15/8 (65% F)
Mean Age [years]	21.03 ± 1.68	21.97 ± 1.87
Average time since last injury [months]	45.30 ± 23.45	n/a
Average time since first injury [months]	54.85 ± 21.58	n/a
Average # concussions	1.55 ± 0.76	n/a
	Sport class (#)	
Collision sport	8 (40%)	6 (26%)
Contact sport	7 (35%)	9 (39%)
Non-contact sport	5 (25%)	6 (26%)
Missing	0 (0%)	2 (9%)

sensitivity to prolonged neurological dysfunctions post-concussion, over the Axon CCAT used by Martini and colleagues (Martini et al., 2017). The incongruent task condition of the Stroop color-word task strongly links to response inhibition (Goghari and MacDonald, 2009; Grandjean et al., 2012; Herd et al., 2006), an element which the Axon CCAT did not include. Computer-based assessments that incorporate elements of response inhibition have demonstrated sensitivity to prolonged concussion related performance changes (e.g., Arata et al., 2019; Dalecki et al., 2019). This difference could be one potential explanation for the distinct findings between our study and the study from Martini and colleagues. In addition, participant demographics such as age and time of concussion sustainment, varied significantly between both studies. Average participant age at concussion sustainment was 17 years for our study compared to 13 years in (Martini et al., 2017). Potentially, due to ongoing brain maturation, the younger participants' brains may have had a larger 'reserve' for compensation, thus mitigating any manifestation of cognitive deficits. This result is consistent with similar research linked to cognitive-motor tasks in youth with concussion history (Dalecki et al., 2019a; Goldman-Rakic, 1987; Paus, 2005, 2010; Paus et al., 1999).

However, the previous assumption about task sensitivity also matches more recent findings linking cognitive functions in adolescents and young adults with a history of concussion. A *meta*-analysis by (Alsalaheen et al., 2017) found no evidence of prolonged cognitive impairments post-injury. However, its assessment was limited to studies that used the ImPACT test only, meaning other studies with potentially more sensitive evaluations were excluded (Alsalaheen et al., 2017). The sensitivity of the ImPACT test on prolonged behavioural and neurological dysfunction has been challenged in recent years (Brown et al., 2015; Dalecki et al., 2016; Schatz et al., 2006), and our findings appear to reinforce this ongoing debate.

While CH participants experienced a greater error rate in the Stroop task than NH participants, we found no significant response time differences between groups for either task (Stroop, D2), suggesting that processing speed was generally not affected (Fig. 1a and 1b). Furthermore, cognitive control deficits in the Stroop task tended to be greater in the incongruent task condition, which required response inhibition (Fig. 1b). Again, this finding emphasizes the notion that high order cognitive functions linked to inhibitory control are potentially more sensitive to concussion related impairments over time. Notably, we discovered similar findings in a companion study that used eye-hand coordination related cognitive-motor integration tasks. The study found that young adult participants with a concussion history from youth struggled with decoupling the naturally aligned eye-hand movement direction (Arata et al., 2019). Suppressing the natural instincts and reflexes that humans have to move their eyes and hands together requires high levels of inhibitory control (Gorbet & Sergio, 2009). Arata and colleagues hand-eye coordination study displayed cognitive-motor integration deficits with movement planning while movement execution values remained intact (Arata et al., 2019). These findings correspond with results of the present study, in that CH participants made significantly more decision-making errors than NH participants while maintaining intact processing speed (i.e., task execution). Both, eye-hand decoupling as well as response inhibition during a Stroop task, heavily rely on well-functioning fronto-parietal networks (Dalecki et al., 2019b; Goghari and MacDonald, 2009; Herd et al., 2006).

The current study found no significant differences in response time or error rate between groups for the D2 task, suggesting that concussion history participants sustained attention levels were not impaired averaging four years post-trauma. This finding is consistent with the majority of previous studies and suggests that prolonged sustained attention deficits may not transfer into young adulthood (Kramer et al., 2008). These findings require further investigation, but could potentially support the notion that task differences and task sensitivity influence have residual effects of brain dysfunction post-injury as asserted by (Martini et al., 2017).

Although there were no significant differences in error rate between groups for the D2-sustained attention task, the D2 error rate within the CH group was positively correlated with time since injury (Fig. 2d, 2e). These results may provide tentative evidence for subtle functional and or structural brain changes over time as a result of brain injury. Alternatively, it could also suggest deficits in the maturation of relevant brain function and or structure during late adolescence or early young adulthood (Tamm et al., 2002). However, the absence of a greater D2-error rate in CH participants (Fig. 2c), as well as the absence of similar relations between performance and time since injury for the Stroop error rate, suggests results should be considered carefully. For clarification, we included the D2-error rate mean baseline of the NH group and their 95% confidence intervals into both graphs (see control group error rate as grey horizontal lines in Fig. 2d, 2e). One might argue that the error rate exceeded the upper confidence interval of the control group in almost all cases after sixty months post-injury. Nonetheless, further increasing the sample size and expanding the participant age range could allow for a more extensive time-course representation of post-incident dynamics.

Furthermore, research has shown that age at first concussion was the strongest predictor of D2 performance in adolescent athletes with a CH (Taylor et al., 2018). Unfortunately, we did not report participant birthdates, which are needed to precisely calculate their age at first concussion. A provisional analysis with estimates of age at first concussion indeed pointed towards a strong relation between age at first concussion and D2 error rate ($R = 0.730$, $p < 0.001$). This would tentatively suggest that age at first concussion may have been an even stronger predictor for sustained attention metrics than time since concussion in our data set. These assumptions underline the need for a more in-depth investigation of the relationships between age, concussion incidence, and cognitive scores in future studies linked to similar cohorts.

In addition, CH participants also experienced diminished immediate memory and concentration levels, along with a higher symptom severity in the SCAT5 test (Tables 1 and 2). Lower concentration and memory scores in the CH group may potentially contribute to decision-making errors in the Stroop task. However, the unaffected sustained attention levels underline that the D2 and SCAT5 cognitive tests seem to measure different functions linked to concentration. This is also represented through assessment duration. The D2 test stretches over 6-minutes and measures sustained attention, while the concentration SCAT5 test consists of two very brief assessments (each around one minute long).

Table 2
Descriptive results of the repeated-measures ANOVA for Stroop with group (Concussion history, No-history) and condition (Congruent, Incongruent), of the one-way ANOVA for Stroop Interference (Incongruent-Congruent), D2 sustained attention, and the SCAT5 test with group (Concussion history, No-history). Abbreviations: RespT = Response Time; Interference = Incongruent – Congruent.

Stroop Test			
Variable	Condition	Concussion history	No-history
RespT [ms]	Congruent	927.9 ± 207.8	868.7 ± 205.9
	Incongruent	1064.8 ± 258.7	974.9 ± 182.3
	Interference	136.9 ± 238.4	124.2 ± 128.8
Error Rate [%]	Congruent	1.57 ± 2.57	1.04 ± 1.63
	Incongruent	6.67 ± 5.72	3.62 ± 2.96
	Interference	4.38 ± 6.04	2.47 ± 3.06

D2 – Sustained Attention Test		
Variable	Concussion history	No-history
Concentration Score [#]	144.25 ± 26.42	142.55 ± 27.09
RespT [ms]	651.3 ± 135.3	670.6 ± 151.0
Error Rate [#]	17.05 ± 12.01	17.41 ± 15.97

SCAT5 Test		
Variable	Concussion history	No-history
Symptoms [#]	7.68 ± 7.48	4.65 ± 4.40
Symptom Severity	17.05 ± 16.62	6.70 ± 6.34
Orientation	4.95 ± 0.22	5.00 ± 0.00
Immediate Memory	14.16 ± 1.30	14.72 ± 0.58
Concentration	3.17 ± 0.99	4.13 ± 0.81
Delayed Recall	3.29 ± 1.21	3.17 ± 1.20

Nonetheless, decision-making during the Stroop task could potentially have been negatively affected by the higher severity of symptoms in the CH group. Executive function performance and decision-making are known to be negatively influenced by the severity of fatigue, headache (s), and sleep quality in healthy participants as well as in other neurological populations (Ceschi et al., 2017; Mavaddat et al., 2000). The higher symptom severity was also positively related with the number of concussions. While this finding is not surprising, all other significant findings linked to behavioral performance outcomes were unrelated to the number of concussions. This may provide further evidence for the notion that symptom severity is sensitive for repeated head-injury (Bryan, 2013), but it may also in turn suggest that lingering behavioral deficits post-injury could be independent from repeated head-trauma. However, this assumption requires further investigation.

Recent studies have also demonstrated the impact of sports classification (i.e., high versus low impact sports) on concussion related behavioral and mental declines (McAllister et al., 2014; Tsushima et al., 2016). While we did not find significant differences between collision, contact, and non-contact sports in our study, we acknowledge that this lack of differences may be related to sample size. On the other hand, using current non-athletes may have reduced the likelihood of sub-concussive blows to the head, as it is well known that athletic populations are at a greater risk for exposure to them (Erlanger, 2015; Johnson, 2014). This, in turn, could have diminished the influence of sports played on concussion related cognitive deficits in our present data set.

Taken together, the results of the present study extend our understanding of sport-related concussion(s) from youth, and their potential impacts on behavioral cognitive outcomes in non-athletic young adulthood. Our findings suggest that executive function, with an emphasis on response inhibition, seemingly proves more sensitive to prolonged cognitive impairments than sustained attention capacity. The brain mechanisms that negatively affected decision-making in the Stroop task did not alter similar task mechanics of sustained attention in the D2 task when performance was directly compared to the control group. However, the sustained attention error rate correlated positively with time

Table 3
Mean results statistical outcomes of the two-way repeated-measures ANOVA for Stroop test response time and error rate, with group (concussion history, no-history), and condition (Congruent, Incongruent), and of the one-way ANOVA for Stroop Interference (Delta Incongruent – Congruent), D2-Test SCAT 5 test scores, with group (concussion history, no-history). Abbreviations: RespT = Response time, RT = Reaction time, MT = Movement time, PL = Path length; ST = Standard condition, CMI = Cognitive-motor integration condition.

variable	group (ConcHist, No-Hist)			condition (Congruent, Incongruent)			group x condition		
	F (1,41)	p - value	η^2	F (1,41)	p - value	η^2	F (1,41)	p - value	η^2
RespT	1.669	0.204	0.039	15.580	0.000	0.275	12.055	0.622	0.006
Error Rate	**4.766**	**0.035**	**0.104**	**31.399**	**0.000**	**0.434**	3.369	0.074	0.076
significant pairwise comparison									
variable	group (ConcHist, No-Hist)								
	F (1,41)	p - value							
Error Rate (incongruent)	**4.989**	**0.031**							
one-way ANOVA									
variable	group (ConcHist, No-Hist)								
	F (1,41)	p - value							
RespT Interference	0.551	0.462							
Error Rate Interference	1.816	0.185							
D2 Sustained Attention test									
Variable	group (ConcHist, No-Hist)								
	F (1,41)	p - value							
D2-score	0.042	0.838							
RespT	0.189	0.666							
Error rate	0.007	0.935							
SCAT5 test									
Variable	group (ConcHist, No-Hist)								
	F (1,36)	p - value							
Symptoms	2.135	0.153							
Symptom Severity	**5.558**	**0.024**							
Orientation	0.946	0.337							
Immediate Memory	**4.469**	**0.042**							
Concentration	**6.547**	**0.016**							
Delayed Recall	0.047	0.829							

since first and time since last concussion. These results should prompt further investigations into the potential long-term consequences of mild traumatic brain injuries in youth.

3.1. Limitations

Our study is currently constrained by its small sample size and limited variability in time-since-incident observations. Thus, increasing the sample size and expanding the participant age range (i.e., to include adults with concussion history from adolescence) would be beneficial for a more solid investigation of the interplay between history of concussion(s) and the time-course of potential cognitive impairments. Despite our study's thorough screening process, we cannot exclude the possibility that unmeasured factors may have confounded our results (Cunningham et al., 2020; Piantella et al., 2020). For example, research revealed that executive function can be influenced by factors such as sleep, physical activity level, socioeconomic status, and race/ethnicity (e.g., Alosco et al., 2019; Lax et al., 2015; Wallace et al., 2020). In the following sections, we discuss the potential influence of these factors in relation to our study.

Executive function can be biased by sleep quality (Gevers et al., 2015), especially in individuals with a concussion history (Oyegbile et al., 2020). Although we did not directly assess sleep quality, an analysis of the items 'Fatigue or low energy' and 'Trouble falling asleep' from the SCAT 5 symptoms severity assessment did not reveal significant differences between study groups or a correlation with D2 error rate in the CH group (all $p > 0.05$). We also did not assess current physical activity levels which can influence executive function as well (Etnier & Chang, 2009). Notably, youth sport participation appears to be a successful predictor of young adult physical activity levels (Telama et al., 2006), and confounding effects of activity level tend to influence executive function processing speed rather than error rate (Etnier & Chang, 2009; Goenarjo et al., 2020). Since we found significant differences between study groups only for error rate, and screening criteria required all participants to be undergraduate students with a history of involvement in sports from adolescence, we are optimistic that the influence of physical activity levels on our study's outcomes were minimal.

Unfortunately, we did not document participant's socioeconomic status and race/ethnicity; thus, we were unable to address their potential confounding effects on cognitive function following head injury (Alosco et al., 2019). However, focusing only on college students may have reduced potential biases linked to these two factors as well. Nevertheless, we acknowledge that future studies should use a more detailed screening process, ideally performed by a medical professional, to further minimize the risk of confounding factors known to be associated with concussion(s) and executive function (Piantella et al., 2020). Another limitation was that participant concussion history was evaluated through self-report assessments. Therefore, there was a greater risk for potential errors about concussion metrics due to participant inaccuracy. Conversely, we used multiple assessments to obtain concussion history information, and participants were excluded from the final analysis if they were unable to provide precise information about their concussion history or if their concussion(s) was not diagnosed by a medical professional. However, we acknowledge that self-report assessments and testing non-athletes pose limitations on medical documentation of concussion history and may increase the risk of undiagnosed injury.

Another limitation centers on the fact that CH participants were shown to have higher levels of symptom severity than NH participants, indicating they were not truly 'asymptomatic,' even though they alleged so prior to testing. Future studies should compare asymptomatic and symptomatic concussion history participants with no history controls. Also, future studies should combine behavioral testing with brain imaging techniques to have the opportunity to relate behavioral outcome deficits to potential brain functional and or structural changes. Previous studies have used functional magnetic resonance imaging to identify deficits for immediate impacts, based on scans of brain structure and activity (Slobounov et al., 2010). Similar approaches could be used to examine intermediate-term effects, while offering a comparison to cognitive and behavioral testing.

3.2. Conclusions

Our results indicate the possibility of prolonged cognitive impairments in young adult, non-athletic college students with a sport-related concussion history from adolescence. It is important to highlight that our study participants gained a sports-related concussion in adolescence but were not active athletes at the time of testing, which separates our study from other experiments focusing exclusively on college athletes. Cognitive impairments were mainly linked to an increased error rate when performing a response inhibition task while processing speed remained intact, providing evidence for less efficient high-order cognitive control. Measures of sustained attention remained intact when compared to no history controls, but sustained attention task error rate correlated positively with greater time since first and last concussion. Prolonged cognitive deficits in young adults averaging four years post-concussion may provide further evidence for subtle functional and or structural brain changes over time.

4. Experimental Procedure

4.1. Participants

Twenty-four college students (21.03 ± 1.68 years.; age range 18–23 yrs.; 14 females) with a self-reported history of a sport-related concussion (CH) ($\mu = 48.31 \pm 11.30$ months post impact, range: 10–90 months) and twenty-four college students (21.97 ± 1.87 yrs.; age range 18–23 yrs.; 14 females) with no history of a concussion (NH) were recruited during 2018 and 2019 at Louisiana State University. Inclusion criteria required both study groups to have a history of involvement in sports on an amateur level only (i.e. college level athletes were not tested). Although all participants included in the study were former athletes, individuals involved in contact sports within 12 months of testing were not utilized. Participants with an undiagnosed concussion history or medical conditions such as attention deficit disorder were also excluded from study. Besides a history of a concussion, all participants involved reported being relatively healthy, without any known existing neurological impairments. Summary statistics of participant's demographics, concussion history information, and sports classification are provided in Table 1. Athletic history within the CH and NH groups included collision sports (e.g., football), contact sports (e.g., soccer), and non-contact sports (e.g., gymnastics). Participant history of sports involvement for both study groups is provided in the full data set in Supplementary file I. A portion of the participants were also involved in a larger companion study that included further testing such as eye-hand coordination performance (data presented elsewhere) (Arata et al., 2019).

4.2. Procedures

All participants were asked to complete a baseline questionnaire to ensure eligibility into the study. Questions about demographics, prior concussion history, current medical conditions, and participation in sports were included in the screening process. Participant concussion metrics were further assessed through SCAT-5, which also included symptom and severity check and the Standardized Assessment of Concussion (SAC). For the SCAT-5 assessment, participants were administered a 22-item list of symptoms and asked to weight each on a 7-point Likert scale (0 being no symptom and 6 being highest severity). The SCAT-5 score was derived as the aggregate number for all symptoms indicated (maximum score of 132). Participant's immediate memory, delayed memory, and concentration were also assessed through the SAC, a standard collection of memory recall tests (Echemendia et al., 2017).

Participants were then given two computerized cognitive assessments, a Stroop color word test and a D2 sustained attention test. Experiments were performed on a 15.6-inch Dell Inspiron 3000 laptop (screen resolution 1366 × 768; 60 Hz), with screen display placed around 75 cm away from the eyes. The Stroop color word task assessed a participant's ability to inhibit prepotent responses and was administered by PsychoPy (version 1.85.01). Four words (blue, green, red, and yellow) were presented on a computer screen in two conditions. In the congruent condition, color and meaning of the word coincided; and in the incongruent condition, color and meaning differed. The assessment involved the presentation of one color word in the center of a screen, with four response possibilities. Participants were instructed to select the text color in which each word was printed, not the meaning of each word. Response options were color-coded using labels attached to arrow keys: blue (↑), green (→), red (↓) and yellow (←). Participants were instructed to select the color key that corresponded with the text color indicated on the screen. Subjects were told to respond as quickly and as accurately as possible; and to rest their index and middle finger, of their dominant hand, upon they keyboard in order to obtain a faster response. Each item was presented on the screen until the participant responded. The program presented a total randomized mix of 48 congruent and 48 incongruent trials to each participant. Average time for test completion was five minutes.

Upon completion of the Stroop task and a rest brake, participants were administered a sustained attention assessment, consisting of a computerized version of the D2 test (Brickenkamp, 2002; Dalecki et al., 2012). Subjects left index finger rested on the 'A' key and their right index finger on the 'D' key. Respondents were presented nine-count sequences containing varying combinations of the letters *d* and *p*, each with 1, 2, 3, or 4 character notations in subscript or superscript form. Labels were affixed to the keyboard letters 'A' and 'D' to provide more intuitive response conditions (*D2* for 'A' and *Not D2* for 'D'). Participants were instructed to press the *D2* key when seeing the letter d surrounded by two commas (regardless of placement), and to press the *Not D2* key otherwise. The ninth response triggered the display of a new sequence and trials terminated after 30 s. Subsequent trials were separated by a break of 0.5 s, for a total of 12 trials. The remaining time for each trial was displayed in the top right corner of the screen, with the trial number in the top left corner of the screen. A rectangular text box framed the target letter, switching to the next letter in the sequence immediately after subjects responded. Participants worked on the sequence from left to right and were reminded to respond as quickly and accurately as possible. Average time for test completion was six minutes.

4.3. Dependent measures

The dependent variables of interest for the Stroop test and the *D2* test were response time (milliseconds), error rate (%), and sustained attention score (for *D2* test only, defined as number of correctly marked minus the number of incorrectly marked D2-target letters). Correctness and response time were analyzed for each trial in each condition (Stroop task only; congruent and incongruent). For calculating interference effects of the Stroop task, data was normalized by subtracting each participants mean score of congruent trials from the incongruent trials. This resulted in delta errors (errors incongruent – errors congruent) and delta response time (RT incongruent – RT congruent). For the Stroop task, response time for all correct responses was averaged for each participant across all trials for each condition (congruent, incongruent), and in the D2 task, averaged across all correct responses made for 'D2′ and 'not D2′. Note that we performed an additional analysis comparing response times of 'D2′ and 'not D2′ responses and did not find significant differences. Thus, we averaged response time across all responses for the main analysis. Dependent variables for the SCAT 5 test were number of symptoms (out of 22), symptom severity (out of 132), as well as scores for immediate memory (out of 15), delayed memory (out of 5), and concentration level (out of 5).

4.4. Statistical analysis

The final data analysis included 20 CH (11 females) and 23 NH (14 females) participants. Five participants were excluded due to task confusion and or concussion history falling outside of screening criteria (e.g., participants were not able to provide precise information about their concussion history). Statistical analysis of all remaining data was performed using one-way and multivariate ANOVA. When significant main or interaction effects were observed, pair-wise comparisons were performed and adjusted for multiple comparisons (Bonferroni). All data was checked for normal distribution (Shapiro-Wilk's test) and sphericity (Mauchly's test) and was Greenhouse-Geisser corrected in case of sphericity violations. Statistical analyses were performed using SPSS statistical software (IBM Inc.), and statistical significance level was set at < 0.05.

In detail, Stroop data (response time, error rate) was analyzed using mixed-measures *ANOVA* with group as between subject factor, and condition (congruent, incongruent) as within subject factor. Stroop interference effects (delta incongruent-congruent for response time and error rate), D2 (sustained attention score, response time, error rate), and SCAT 5 data (number of symptoms, symptom severity, immediate memory, delayed memory, concentration) were analyzed using One-Way *ANOVA* with group (concussion history, no history) as between subject factor. Correlation analysis (Pearson, 2-tailed) was used to determine the relation between performance variables (Stroop, D2, and SCAT 5) and time since last concussion (months) and time since first concussion (months). Additionally, separate analyses using sex, number of concussions, and sport classification (collision sport, contact sport, non-contact sport) were run to test for sex, number of concussions, or sport related behavioral differences.

CRediT authorship contribution statement

Abigail L. Caffey: Investigation, Data curation, Visualization, Writing - original draft. **Marc Dalecki:** Investigation, Conceptualization, Methodology, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.brainres.2021.147570.

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