Effects of Concussion on Attention and Executive Function in Adolescents

DAVID HOWELL[1], LOUIS OSTERNIG[1], PAUL VAN DONKELAAR[2], ULRICH MAYR[3], and LI-SHAN CHOU[1]

[1]Department of Human Physiology, University of Oregon, Eugene, OR; [2]School of Health and Exercise Sciences, University of British Columbia, Kelowna, BC, CANADA; and [3]Department of Psychology, University of Oregon, Eugene, OR

ABSTRACT

HOWELL, D., L.-S. OSTERNIG, P.-S. VAN DONKELAAR, U.-S. MAYR, and L.-S. CHOU. Effects of Concussion on Attention and Executive Function in Adolescents. *Med. Sci. Sports Exerc.*, Vol. 45, No. 6, pp. 1030–1037, 2013. **Background**: Head trauma in adolescents has been linked with deficits in attention and executive function that can compromise the performance of everyday tasks. Although previous research has examined this issue using computerized neuropsychological testing, little work has been done using laboratory-based measurements of attention and executive function in this population. A longitudinal analysis of recovery patterns of these measures among adolescents is central to understanding the effects of concussions across the age spectrum. **Purpose**: This study prospectively and longitudinally examined laboratory-based measures of attention and executive function in concussed adolescents sequentially during a 2-month period after injury. **Methods**: Two measures of attention and executive function, the Attentional Network Test and the Task-Switching Test, were administered to 20 concussed adolescents within 72 h postinjury as well as at 1 wk, 2 wk, 1 month, and 2 months postinjury. Twenty healthy, matched control subjects were similarly assessed at the same time intervals. Data were analyzed by two-way, mixed-effects ANOVA to determine the effect of group and time on the dependent variables. **Results**: Compared with control subjects, the concussed group exhibited a significantly greater switch cost on the Task-Switching Test (P = 0.038, mean difference value = 38 ms) and a significantly greater reaction time for the Attentional Network Test conflict effect component (P = 0.015, mean difference value = 34 ms) for up to 2 months after injury. **Conclusions**: Concussed adolescents have difficulty recovering executive function after injury and may require extended recuperation time before full recovery is achieved. Evaluations focusing on attention and executive function can be useful additions in the assessment and follow-up after head injury. **Key Words:** SPORT CONCUSSION, EXECUTIVE FUNCTION, ATTENTION, TASK SWITCH

The Centers for Disease Control and Prevention have described brain injury as a silent epidemic (20), which suggests that mild traumatic brain injury (mTBI) has become a public health problem, the magnitude and the effect of which are underestimated by current surveillance systems. Many of the mTBI that occur in young adults and adolescents take place in the context of sport activities (19) and thus fall into the category of sports-related concussion. It has been found that deficits from this injury may last longer than those reported by the patient and may be present even after the return to unrestricted activity (3,27,38), suggesting that current clinical assessment tools may lack sufficient sensitivity to accurately track functional recovery.

Address for correspondence: Li-Shan Chou, Ph.D., Department of Human Physiology, 122 Esslinger Hall, 1240 University of Oregon, Eugene, OR 97403; E-mail: chou@uoregon.edu.
Submitted for publication August 2012.
Accepted for publication November 2012.

0195-9131/13/4506-1030/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0b013e3182814595

Executive function has classically been defined as the capacity to flexibly plan purposeful behavior (21) and is considered to be responsible for the synthesis of external stimuli and preparation for action (24). Attention processes are believed to be important elements of executive function (1) as well as tasks requiring deliberate attention including decision making, troubleshooting, novel sequence of action, and tasks considered technically difficult (31). These functions can be tested by using a variety of laboratory-based tasks in which an individual must generate one of two or more responses in a context-dependent manner. Performance on such tasks has been shown to be deficient in college age students who have suffered a concussion for up to 1 month after injury (15). Previous literature suggests that tests that focus on executive function in individuals recovering from mild to moderate TBI may be useful in predicting outcome from injury (16).

Although the adolescent brain has not yet reached full maturation (8,23,32) and is in a period of rapid development from approximately 14–16 yr old (1,13), few studies have focused on the long-term consequences of concussion in adolescents. In a retrospective study assessing sport concussions in children, adolescents, and adults, Baillargeon et al. (2) reported that adolescents displayed persistent neurophysiological deficits that were present at least 6 months after a concussion and were more sensitive to the consequences of concussion than that in adults. The adolescent age group has been reported to be vulnerable to the effects of concussion due to the continued development of the frontal region of the brain (22), which is responsible for working memory and executive function. A head injury during this critical development time could result in deleterious effects on these cognitive components (2). Because executive function is considered to encompass the highest levels of human functioning (9) and attention processes are considered to play important roles in the control of action (31), the monitoring of these cognitive elements in a population particularly vulnerable to the effects of concussion is warranted.

Recognizing how such cognitive functions are affected by and recover after concussion in adolescents can help medical personnel better identify incomplete recovery, which is a predictor of recurrence of brain injury (14), and provide much needed additional data for the reintegration to preinjury levels of mental and physical activities. Therefore, the purpose of this study was to prospectively and longitudinally examine measures of attention and executive function in concussed adolescents and healthy, matched control subjects within a 72-h acute postinjury interval and for the subsequent 2 months postinjury.

The hypothesis of this investigation, based on prior research in young adults, was that adolescents would be significantly affected by concussion on tests of attention and executive function for up to 1 month postinjury when compared with a healthy group of age-matched control subjects who underwent the same testing timeline and protocol.

METHODS

Forty high school students participating in school sports at three local high schools (36 men/4 women) were identified and recruited for testing. Twenty of the participants were identified by specialized health professionals (certified athletic trainer/physician) as suffering a concussion consequent to sport participation. Concussion was defined according to the 3rd International Statement on Concussion in Sport as an injury caused by a direct blow to the head, face, neck, or elsewhere in the body with an impulsive force transmitted to the head resulting in impaired neurologic function and acute clinical symptoms (28). Each concussed subject in the study was matched with a healthy control subject (n = 20) by sex, height, mass, age, and sport (Table 1). Prospective control subjects were identified by certified athletic trainers at the high school from which the matched concussed subject was a student. Matching criteria were confirmed at the laboratory test site.

Each concussed subject was removed from the injury site on the day of injury and did not return to preinjury levels of physical activity until cleared by a physician in accordance with state law. Exclusion criteria for concussed and control subjects included the following: 1) lower extremity deficiency or injury, which may affect normal gait patterns; 2) history of cognitive deficiencies, such as permanent memory loss or concentration abnormalities; 3) history of three or more previous concussions; 4) loss of consciousness from the concussion lasting more than 1 min; 5) history of attention deficit hyperactivity disorder; or 6) a previously documented concussion within the past year. Individuals with a history of three or more previous concussions were ineligible to participate to ensure, to the extent possible, the exclusion of subjects experiencing chronic mTBI. Subjects who suffered loss of consciousness for more than 1 min were excluded from participation in the study because that sign is believed to play a role in concussion management modification (28).

TABLE 1. Subject characteristics (group mean ± SD).

Characteristic	Concussed Subjects	Control Subjects
Age (yr)	15.3 ± 1.3	15.6 ± 1.0
Height (cm)	173.7 ± 6.4	173.4 ± 8.1
Mass (kg)	74.8 ± 16.6	70.7 ± 13.6
Sex (M/F)	18/2	18/2
Sport	Football: 15	Football: 15
	Soccer: 3	Soccer: 2
	Volleyball: 1	Volleyball: 1
	Wrestling: 1	Wrestling: 1
	Basketball: 0	Basketball: 1

Before data collection, the institutional review board reviewed and approved the protocol of the current study. All subjects and parent/guardian (if younger than 18 yr) provided informed consent. Permission was also granted by the respective school districts to conduct testing with student participants.

A prospective, repeated-measures design was used in which each subject reported to the laboratory and was tested within 72 h of sustaining a concussion as well as on four subsequent testing days at the following time increments: 1 wk, 2 wk, 1 month, and 2 months postinjury. Control subjects were similarly tested according to the same time schedule. The Attentional Network Test (ANT [12]) and the Task-Switching Test (TST), adapted from Mayr (25), were administered separately and individually to each study participant in a visually enclosed space free from distracting noise and other people. The components of cognitive function each test measures have been shown to be sensitive to the effects of concussion (4,15). In addition, to better understand the clinical presentation of each subject, a concussion symptom checklist was administered, which assessed 22 symptoms on a six-point Likert scale adapted from McCrory et al. (28).

The ANT was originally designed to evaluate abnormalities arising in cases of brain injury, stroke, schizophrenia, and attention deficit disorder (12). It probes the efficiency of three distinct attentional components: alerting (alerting effect), spatial orientation (orienting effect), and executive function (conflict effect) by assessing the relative change in reaction time (RT) to differing precue and stimulus configurations (12). Event-related functional magnetic resonance imaging has been used to explore the brain areas involved in the three attention systems targeted by the ANT (11). The results suggested that the functional contrasts within the ANT tended to differentially activate three separable anatomical networks related to the components of attention. The conflict effect has been shown to be significantly affected by mTBI up to 1 month postinjury, and the orienting effect has been shown to be affected within the first 2 d postinjury in young adults (15), but these effects have yet to be systematically studied in concussed adolescents.

For the past 10 yr, versions of the ANT have been used in more than 60 publications dealing with a wide range of topics and methods, including development, neuroimaging, pharmacology, genetics, psychiatric disorders, brain damage, and individual differences (17). Recently, Ishigami and Klein (17) tested the reliability of the ANT on healthy young adults for the 10 testing sessions. They observed learning effects during the first few sessions for the executive component (conflict effect) and reported that reliability improved as more sessions were included in the analysis. Between sessions 1 and 2, they found correlations of −0.02, 0.57, and 0.86 and when combining sessions 1–10 (using a modified split-half correlation analysis) of 0.80, 0.65, and 0.93 for the alerting, orienting, and executive components, respectively. It was concluded that the ANT was robust after multiple sessions and suitable for applications requiring repeated testing. Because of the noted practice effects, it was suggested that controls are warranted in some designs.

In the ANT, the subject fixates on a cross in the center of a computer screen and responds as quickly as possible by pressing one of two arrow keys, indicating the direction (left or right) of a central arrow presented either directly above or below the cross (Figs. 1A and 1B). The alerting effect is examined by determining the RT difference between trials in which a warning cue (asterisk) precedes the arrow stimulus versus trials in which the warning cue does not precede the arrow stimulus (Fig. 1C). The orienting effect is examined by the RT difference between trials, in which the warning cue indicates the location of the arrow stimulus (above or below the fixation cross) versus trials in which the warning cue does not provide such spatially relevant information (Fig. 1D). Finally, the conflict effect is assessed by the RT difference between trials in which the arrow stimulus is

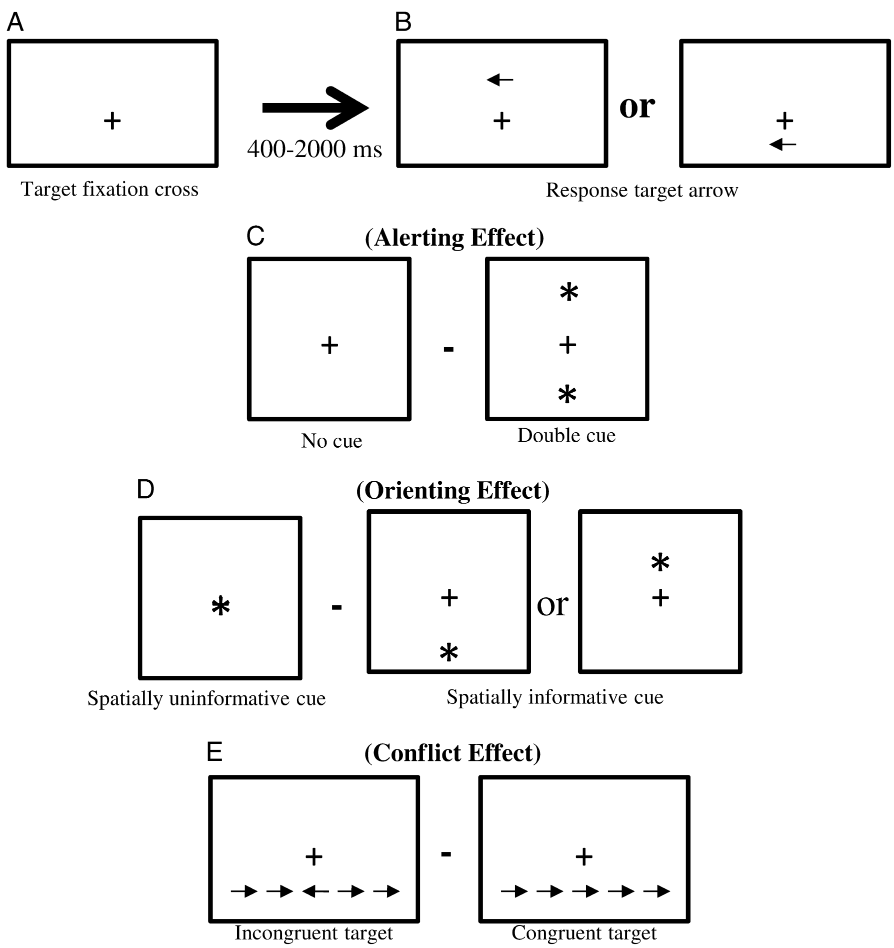


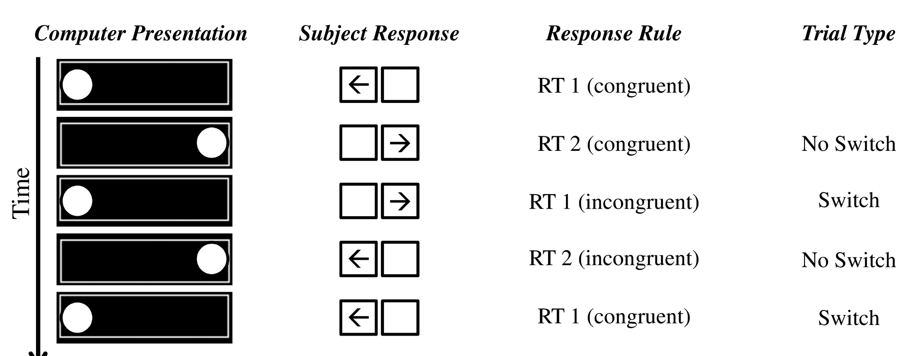
FIGURE 1—ANT: the sequence of events during trials. Subjects focus on the fixation cross and are instructed to respond by pressing the keyboard arrow (left or right) corresponding to the direction of a target arrow when presented directly above or below the cross (A and B). The asterisk is a precue (C and D), which gives information about when (alerting) or where (orienting) the target will appear. Flanker arrows (E) may be presented in configurations which test conflict and nonconflict effects.

accompanied on either side by two congruent flanker arrows (i.e., arrows pointing in the same direction) versus trials in which the arrow stimulus is accompanied on either side by two incongruent flanker arrows (i.e., arrows pointing in the opposite direction; Fig. 1E). Thus, the effect is measured by the RT difference between the two conditions presented for each of the three networks (alerting, orienting, and conflict). A greater RT difference score between groups/testing days indicates poorer performance on that attentional network. Participants first completed a series of 24 practice trials with visual accuracy feedback; they then completed two blocks of experimental trials made up of 96 trials (4 precue conditions $\times$ 2 target locations $\times$ 2 target directions $\times$ 3 flanker conditions $\times$ 2 repetitions) for a total of 192 experimental trials.

The TST uses a paradigm that specifically tests the ability to flexibly switch between competing task or stimulus–response rules (33). The primary dependent variable is the *switch cost*, which is the difference score between the response time from trials on which the task changes (i.e., switch trials) and trials on which the task stays the same (i.e., no-switch trials). Switch costs across different task pairs correlate highly with each other (25,30), suggesting that these costs (a) can be assessed reliably and (b) are independent of the primary task. Further, numerous studies have found that switch costs reflect an executive function that is largely independent of other executive abilities, such as the resolution of conflict or working memory (30). Previous work has found that task-switching ability is highly sensitive to mTBI in adults (4) but has not been studied in the concussed adolescent population. The task-switching paradigm has been used to study executive functions in the context of cognitive development, cognitive aging, and brain imaging (29). In addition, task switching has been used in studies of a wide array of clinical disorders, including attention deficit hyperactivity disorder, Parkinson's disease, and frontal lobe injury (29). The specific paradigm used within the current study design has been documented as a valid way to examine executive functioning and is reliable across testing sessions (33). Rogers and Monsell (33) demonstrated that extra practice did little to increase subject performance when repeat testing occurred, indicating test stability between testing days.

For the current TST, subjects were required to switch between responding congruently and incongruently to the position of a visual stimulus on every second trial in a sequence (25). The subjects responded to the position of a circle presented in a horizontally configured rectangular box (Fig. 2) by pressing the right or left arrow key on a standard computer keyboard as quickly and accurately as possible. In the congruent case, the subject indicated the left or right position of the circle by pressing the corresponding arrow key. In the incongruent case, the subject pressed the opposite key (i.e., left arrow key for right target and *vice versa*). The subject alternated between congruent and incongruent responses on every second trial throughout the sequence of four blocks of 52 trials (208 total trials). If an incorrect response was generated, a visual display was presented to remind the subject which rule (congruent or incongruent) was required to respond correctly. The dependent variable of interest was the "switch cost." This is defined as the difference in RT between "stay" trials, in which the subject did not switch from responding congruent or incongruently (or *vice versa*), and "switch" trials, in which the subject did switch from responding congruently to incongruently (or *vice versa*). Therefore, the switch cost is a measurement of the difference in response time during trials where the rule switched compared with trials where the rule stayed the same. A higher switch cost indicates greater difficulty in adhering to the congruent/incongruent rules. Only trials in which an accurate response was generated were included in the calculation of the switch cost.

Data were analyzed by two-way, mixed-effects ANOVA to determine the effect of group (concussed vs controls), time (72 h, 1 wk, 2 wk, 1 month, and 2 months), and the interaction effects on each of the dependent variables (alerting, orienting, and conflict effects and switch cost). For all omnibus tests, significance was set at $P < 0.05$. Follow-up



Switch Cost = Mean Accurate RT2 – Mean Accurate RT1

FIGURE 2—TST: The subject responds to the position of the circle within the rectangle by pressing the arrow key in either a congruent or incongruent manner, alternating every two trials. The switch cost is calculated as the mean accurate response time difference of trials, which repeat congruent/incongruent responses (no switch) and those which switch between congruent/incongruent responses (switch). The performance differences between trial types are commonly used as measures of executive function ability.

CLINICAL SCIENCES

pairwise comparisons were then examined using the Bonferroni procedure to control family-wise type I error. All statistical analyses were performed using the Statistical Package for the Social Sciences (version 20; SPSS Inc., Chicago, IL).

RESULTS

The concussion subjects were tested within 3 d of injury (mean ± SD = 2.15 ± 0.75 d). After the initial testing took place, each participant returned for testing in the following increments: 8 ± 1.8, 17 ± 3.6, 30 ± 2.6, and 59 ± 3.5 d after injury. Control subjects began participation during the same sport season as their matched concussed subject. After the initial testing session the control subjects returned for testing in the following time increments: 8 ± 2.1, 16 ± 4.5, 30 ± 3.7, and 57 ± 6.4 d after the initial testing session. No significant demographic group differences were observed between the concussion and the control group (Table 1). In one case, a direct sport match was not obtained. The evaluation of clinical symptoms between the concussed and control group revealed a significant time by group interaction (P < 0.001). Follow-up pairwise comparisons revealed that concussed subjects exhibited a significantly higher symptom score than controls at the following time points (mean ± SD): 72 h (concussion = 43.0 ± 25.1, control = 4.3 ± 4.2; P < 0.001), 1 wk (concussion = 30.8 ± 25.2, control = 2.5 ± 2.7; P < 0.001), and 2 wk (concussion = 24.1 ± 22.1, control = 4.1 ± 8.9; P = 0.001). Those differences were no longer statistically significant at the 1-month (concussion = 12.6 ± 14.3, control = 3.1 ± 4.5; P = 0.010) or 2-month (concussion = 11.3 ± 19.8, control = 4.2 ± 6.3; P = 0.149) time points, indicating symptom resolution for concussed subjects on average between the 2-wk and 1-month testing period.

The evaluation of the alerting effect of the ANT demonstrated no significant differences between groups or testing days, and no interactions were present (Fig. 3A; interaction effect P = 0.516, main effect of group P = 0.323, main effect of time P = 0.223). Similarly, the evaluation of the orienting effect of the ANT revealed no differences between groups or testing days, and no interactions were present (Fig. 3B; interaction effect P = 0.258, main effect of group P = 0.236, main effect of time P = 0.266). The analysis of the ANT conflict effect revealed a significant main effect of group (P = 0.015, effect size = 0.192, mean difference value = 34 ms), with the concussed group showing a significantly greater RT difference than controls, indicating a greater conflict effect. A main effect of time was also found to be significant (P < 0.001; Fig. 3C), but with no significant interaction between group and time (P = 0.308). Similar to the conflict effect, the TST switch cost (RT difference) was greater for the concussed group (P = 0.038, effect size = 0.125, mean difference value = 38 ms). A main effect of time (P < 0.001; Fig. 4) was also found to be significant, but with no significant interaction between group and time (P = 0.253).

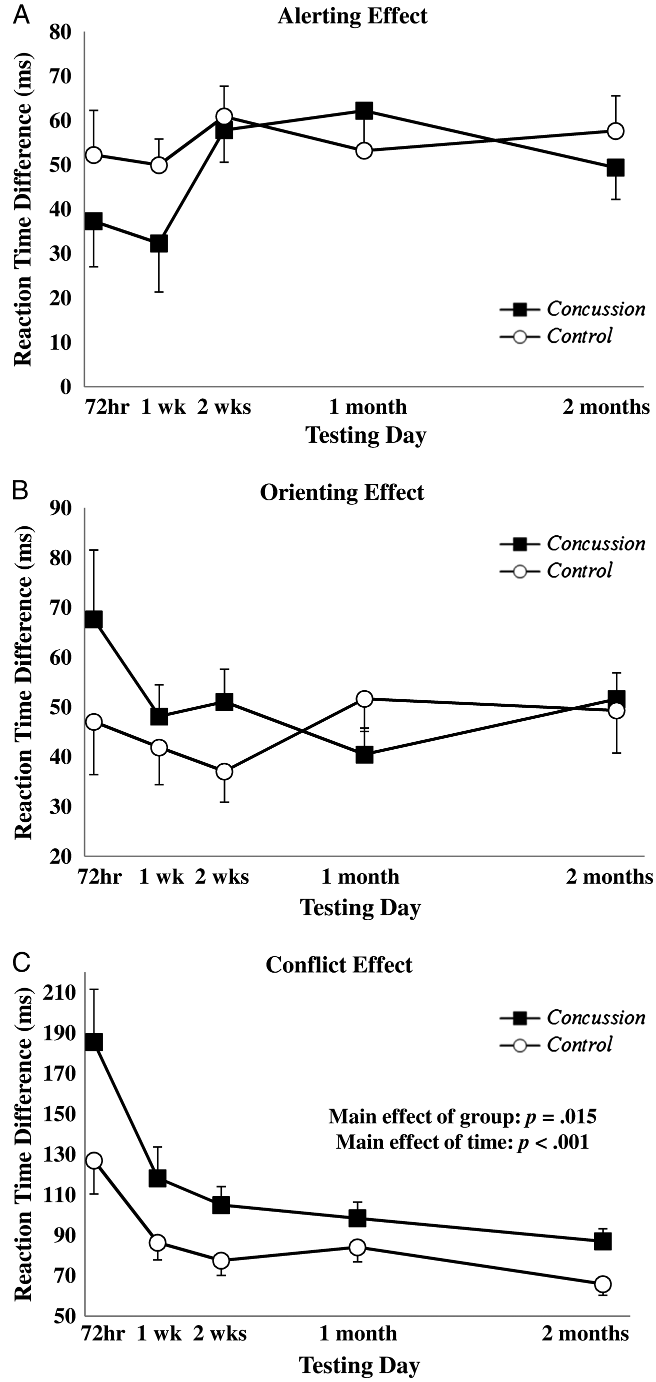


FIGURE 3—Mean + SE for performance on the ANT across the 2-month testing period: alerting effect (A), orienting effect (B), and conflict effect (C). The main effects of group and time were observed for the conflict effect, whereas no significant main effects or interactions were found for the alerting or orienting effects.

Observation of the recovery curves for the conflict effect and switch cost data revealed improving scores for the first 2 wk of testing for the control subjects, suggesting a practice/learning effect on these measures (Figs. 3C and 4). Similarly shaped recovery curves were evident for the concussed subjects for the same period; however, their scores

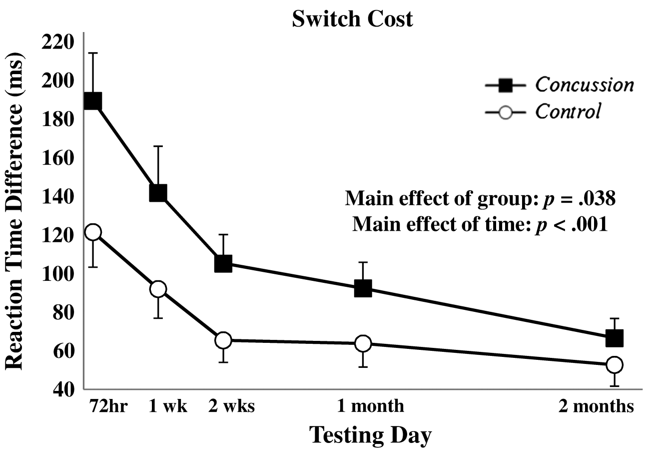


FIGURE 4—Mean +SE for the switch cost, the evaluation of executive function by the TST. The mean RT difference between a switch trial and a no-switch trial for individuals with concussions and controls across the 2-month period of testing is displayed. Main effects of group and time were observed for this measurement.

remained significantly different from the controls throughout the testing period.

DISCUSSION

This investigation was a longitudinal analysis of two cognitive tests which examined how attention and executive function were influenced by concussion in adolescents. The results demonstrated that executive function as assessed in both the ANT and TST was disrupted in concussed adolescents for up to 2 months after injury when compared with a healthy cohort of matched control subjects. By contrast, the alerting and orienting components of attention were not affected by concussion.

The ANT conflict effect appeared to be considerably disrupted by concussion as the injured group had difficulties ignoring irrelevant information contained in the incongruent target configurations. This resulted in significantly longer RT scores than controls for this measure throughout the testing period. These findings are consistent with those of Halterman et al. (15), who found the ability to focus while ignoring irrelevant but conflicting stimuli was impaired up to 1 month after concussion in young adults when compared with matched controls. In the present study, this impairment was evident in the concussed adolescent group for up to 2 months postinjury. This impairment was observed for an extended period when compared with results from the clinical symptom inventory, as the resolution of symptoms typically occurred between 2 wk and 1 month after injury.

Previous reports indicate that the ANT-orienting effect was negatively affected in young adults with concussion during the first 48 h after injury (15). In contrast, the present study detected no differences between groups at any time points for the orienting effect. This may be due to a difference in subject age, or that the current study included those whose initial testing time was up to 72 h after injury, thus extending the amount of potential initial recovery from injury. However, the difference between healthy and concussed subjects at 72 h postinjury appears to be similar to those previously reported but statistically insignificant. In addition, the lack of any differences between groups or across testing days for the alerting effect is consistent to previous findings in young adult subjects (15). The lack of significant differences between groups in both the orienting and alerting effects may also indicate that no preexisting attentional deficits were present between healthy and concussed subjects.

Previous literature identifies the anterior cingulate cortex and prefrontal cortex regions of the brain as the areas responsible for conflict resolution (10). The anterior cerebral structures are believed to play a role in the ability to focus attention on relevant stimuli while filtering out extraneous information (36,37). As these frontal regions of the brain are among the last to develop (35), this region of the adolescent brain may be susceptible to concussion and deficits may last longer in this population than older age groups (2).

In the TST, the reaction time cost of accurately switching from one task to another was significantly greater for the concussed group than the controls throughout the 2-month testing period. Task-switching tasks have previously been shown to probe executive function by requiring subjects to flexibly plan responses in a context-dependent manner (26). Given that efficient and accurate performance of motor skills involves reaction to and behavior produced from multiple stimuli occurring simultaneously, the task-switching paradigm may provide useful information on the demands of changing internal cognitive configurations (25), which must be addressed during multitasking endeavors, such as in academic, job-related, and sport activities.

Executive function has been considered to be responsible for the synthesis of external stimuli and preparation of action (24), and individuals with mTBI often struggle to maintain or appropriately allocate their attentional resources while performing one or more concurrent tasks (5–7,34). The results of this study suggest that tests which isolate components of executive function (ANT and TST) are sensitive to the effects of concussion in adolescents and reveal cognitive deficiencies that may last for at least 2 months after concussion. These data suggest that executive function testing may be a highly useful assessment to identify disturbances and track recovery following concussion for the adolescent population. As task switching and conflict resolution are central to any activity that involves distribution of attention, this type of testing may help to understand how well an individual will respond to such a demand when required to do so. The identification of executive function disruption may help to assist in the assessment of recovery from concussion.

In this study, both the concussed and control subjects displayed improvements in the ANT conflict effect and TST switch cost across the 2-month testing period, indicating that performance on both tasks got better with practice and/or learning. Similar practice effects were observed for the first few days of testing on the ANT conflict effect by Ishigami and Klein (17,18), and as a consequence, they noted the need for a control group in some designs. Given the significant between-group differences and the lack of an interaction between the concussed and the control groups across the testing sessions, these tasks appear to remain sensitive to the disruptions in executive function induced by concussion for up to 2 months postinjury.

The prospective study design and strict subject inclusion criterion related to recruiting and beginning testing within 72 h after injury was a limitation of this study as it resulted in the loss of some potential concussed subjects who were unable to enroll in the study as they could not report for testing within this initial 72-h time frame. However, there was no attrition of any of the 40 subjects during testing. This study was also limited in that no subject baseline data were reported. The inclusion of individually matched healthy control subjects to which the concussed population was compared for the same testing periods countered this limitation to some extent. Although all injured subjects were considered to have sustained a mTBI (concussion) as defined by the 3rd International Statement on Concussion in Sport (28), there undoubtedly was variability in the extent of the injury possibly due to different mechanisms of injury. This variability was mitigated by the exclusion criteria.

CONCLUSION

On the basis of the findings of this study, concussed adolescents appear to have difficulty recovering executive function after injury and may require extended recuperation before full recovery is achieved. Evaluations focusing on attention and executive function can be useful additions in the assessment and follow-up after head injury.

This work was supported by the National Athletic Trainers Association Master's Level Grant, the Veterans Administration subcontract awards (grant nos. A4842C8 and A4843C), the Translational Research Award from the University of Oregon and Peace Health Oregon Region, and the Department of Defense–TATRC Award (grant no. W81XWH-11-1-0717).

The authors acknowledge Jim Becker, Scott Breloff, and Michael Kado in their assistance with data collection. The authors declare no conflicts of interest. The results of the present study do not constitute an endorsement by the American College of Sports Medicine.

REFERENCES

1. Anderson V, Jacobs R, Anderson PJ. *Executive Functions and the Frontal Lobes: A Lifespan Perspective*. New York:Taylor & Francis US; 2008. pp. 24–56.
2. Baillargeon A, Lassonde M, Leclerc S, Ellemberg D. Neuropsychological and neurophysiological assessment of sport concussion in children, adolescents and adults. *Brain Inj*. 2012;26(3): 211–20.
3. Broglio SP, Macciocchi SN, Ferrara MS. Neurocognitive performance of concussed athletes when symptom free. *J Athl Train*. 2007;42(4):504–8.
4. Brooks J, Fos LA, Greve KW, Hammond JS. Assessment of executive function in patients with mild traumatic brain injury. *J Trauma*. 1999;46(1):159–63.
5. Chan RCK. Attention deficits in patients with persisting postconcussive complaints: a general deficit or specific component deficit? *J Clin Neuropsychol*. 2002;24(8):1081–93.
6. Chan RCK, Hoosain R, Lee TMC, Fan YW, Fong D. Are there sub-types of attentional deficits in patients with persisting postconcussive symptoms? A cluster analytical study. *Brain Inj*. 2003;17(2):131–48.
7. Cicerone KD. Attention deficits and dual task demands after mild traumatic brain injury. *Brain Inj*. 1996;10(2):79–89.
8. Daniel JC, Olesniewicz MH, Reeves DL, et al. Repeated measures of cognitive processing efficiency in adolescent athletes: implications for monitoring recovery from concussion. *Neuropsychiatry Neuropsychol Behav Neurol*. 1999;12(3):167–9.
9. David AS. Frontal lobology: psychiatry's new pseudoscience. *Br J Psychiatry*. 1992;161:244–8.
10. Fan J, Flombaum JI, McCandliss BD, Thomas KM, Posner MI. Cognitive and brain consequences of conflict. *Neuroimage*. 2003; 18(1):42–57.
11. Fan J, McCandliss BD, Fossella J, Flombaum JI, Posner MI. The activation of attentional networks. *Neuroimage*. 2005;26(2):471–9.
12. Fan J, McCandliss BD, Sommer T, Raz A, Posner MI. Testing the efficiency and independence of attentional networks. *J Cogn Neurosci*. 2002;14(3):340–7.
13. Fischer KW, Rose SP. Dynamic growth cycles of brain and cognitive development. In: *Developmental Neuroimaging: Mapping the Development of Brain and Behavior*. San Diego (CA): Academic Press; 1996. pp. 263–79.
14. Guskiewicz KM, Weaver NL, Padua DA, Garrett WE. Epidemiology of concussion in collegiate and high school football players. *Am J Sports Med*. 2000;28(5):643–50.
15. Halterman CI, Langan J, Drew A, et al. Tracking the recovery of visuospatial attention deficits in mild traumatic brain injury. *Brain*. 2006;129(3):747–53.
16. Hartikainen KMW. Persistent symptoms in mild to moderate traumatic brain injury associated with executive dysfunction. *J Clin Exp Neuropsyc*. 2010;32(7):767–74.
17. Ishigami Y, Klein RM. Repeated measurement of the components of attention using two versions of the Attention Network Test (ANT): stability, isolability, robustness, and reliability. *J Neurosci Methods*. 2010;190(1):117–28.
18. Ishigami Y, Klein RM. Repeated measurement of the components of attention of older adults using the two versions of the attention network test: stability, isolability, robustness, and reliability. *Front Aging Neurosci*. 2011;3(17):1–13.
19. Kelly J. Sports-related recurrent brain injuries—United States. *MMWR Morb Mortal Wkly Rep*. 1997;46(10):224–7.
20. Langlois J, Marr A, Mitchko J, Johnson R. Tracking the silent epidemic and educating the public: CDC's traumatic brain injury-associated activities under the TBI Act of 1996 and the Children's Health Act of 2000. *J Head Trauma Rehab*. 2005; 20(3):196–204.
21. Lezak MD. *Neuropsychological Assessment*. 4th ed. New York: Oxford University Press; 2004. p. 35.
22. Luna B, Garver KE, Urban TA, Lazar NA, Sweeney JA. Maturation of cognitive processes from late childhood to adulthood. *Child Dev*. 2004;75(5):1357–72.
23. Luna B, Padmanabhan A, O'Hearn K. What has fMRI told us about the development of cognitive control through adolescence? *Brain Cognition*. 2010;72(1):101–13.

24. Luria AR. *The Working Brain: An Introduction To Neuropsychology*. Middlesex (UK):Basic Books; 1976. pp. 249–50.
25. Mayr U. What matters in the cued task-switching paradigm: tasks or cues. *Psychon Bull Rev*. 2006;3:794–9.
26. Mayr U, Bell T. On how to be unpredictable: evidence from the task-switching paradigm. *Psychol Sci*. 2006;17(9):774–80.
27. McClincy MP, Lovell MR, Pardini J, Collins MW, Spore MK. Recovery from sports concussion in high school and collegiate athletes. *Brain Inj*. 2006;20(1):33–9.
28. McCrory P, Meeuwisse W, Johnston K, et al. Consensus statement on concussion in sport: the 3rd International Conference on Concussion in Sport Held in Zurich, November 2008. *J Ath Train*. 2009;44(4):434–48.
29. Minear M, Shah P. Training and transfer effects in task switching. *Mem Cognition*. 2008;36(8):1470–83.
30. Miyake A, Friedman NP. The nature and organization of individual differences in executive functions four general conclusions. *Curr Dir Psychol Sci*. 2012;21(1):8–14.
31. Norman DA, Shallice T. Attention to action: willed and automatic control of behavior. *Cognitive Neuroscience: A Reader*. 1991;376.
32. O'Hare ED, Lu LH, Houston SM, Bookheimer SY, Sowell ER. Neurodevelopmental changes in verbal working memory load-dependency: an fMRI investigation. *Neuroimage*. 2008;42(4):1678–85.
33. Rogers RD, Monsell S. Costs of a predictable switch between simple cognitive tasks. *J Exp Psychol Gen*. 1995;124(2):207–31.
34. Spikman J, van Zomeren A, Deelman B. Deficits of attention after closed-head injury: slowness only? *J Clin Exp Neuropsychol*. 1996;18:755–67.
35. Spreen O, Risser AH, Edgell D. *Developmental Neuropsychology*. Oxford University Press. 1995. p. 50.
36. Stuss DT, Shallice T, Alexander MP, Picton TW. A multidisciplinary approach to anterior attentional functions. *Ann N Y Acad Sci*. 2006;69(1):191–212.
37. Stuss DT, Binns MA, Murphy KJ, Alexander MP. Dissociation within the anterior attentional system: effects of task complexity and irrelevant information on reaction time speed and accuracy. *Neuropsychology*. 2002;16(4):500–13.
38. Van Kampen DA, Lovell MR, Pardini JE, Collins MW, Fu FH. The "value added" of neurocognitive testing after sports-related concussion. *Am J Sports Med*. 2006;34(10):1630–5.