Concussion in Professional Football: Recovery of NFL and High School Athletes Assessed by Computerized Neuropsychological Testing—Part 12

Elliot J. Pellman, M.D.
ProHEALTH Care Associates, LLP, Lake Success, New York

Mark R. Lovell, Ph.D.
Department of Orthopaedics and Sports Medicine, University of Pittsburgh Medical Center, Pittsburgh, Pennsylvania

David C. Viano, Dr. Med., Ph.D.
ProBiomechanics LLC, Bloomfield Hills, Michigan

Ira R. Casson, M.D.
Department of Neurology, Long Island Jewish Medical Center, New Hyde Park, New York
Department of Neurology, Albert Einstein College of Medicine, Bronx, New York

Reprint requests:
David C. Viano, Dr. Med., Ph.D., ProBiomechanics LLC, 265 Warrington Road, Bloomfield Hills, MI 48304-2952.
Email: dviano@comcast.net

Received, February 14, 2005.
Accepted, May 13, 2005.

OBJECTIVE: Acute recovery from concussion (mild traumatic brain injury) is assessed in samples of NFL and high school athletes evaluated within days of injury.

METHODS: All athletes were evaluated within days of injury using a computer-based neuropsychological test and symptom inventory protocol. Test performance was compared to preinjury baseline levels of a similar but not identical group of athletes who had undergone preseason testing. Statistical analyses were completed using Multivariate Analysis of Variance (MANOVA).

RESULTS: NFL athletes demonstrated a rapid neuropsychological recovery. As a group, NFL athletes returned to baseline performance in a week with the majority of athletes having normal performance two days after injury. High school athletes demonstrated a slower recovery than NFL athletes.

CONCLUSION: Computer-based neuropsychological testing was used within the overall medical evaluation and care of NFL athletes. As found in a prior study using more traditional neuropsychological testing, NFL players did not demonstrate decrements in neuropsychological performance beyond one week of injury. High school players demonstrated more prolonged neuropsychological effects of concussion.

KEY WORDS: Concussion, Neuropsychological testing, Sport injury, Traumatic brain injury

Neurosurgery 58:263-274, 2006 DOI: 10.1227/01.NEU.0000200272.56192.62 www.neurosurgery-online.com

The last decade has witnessed the rapid development of new and innovative concussion (mild traumatic brain injury, MTBI) management strategies in the National Football League (NFL). These efforts have been endorsed by the Commissioner's office and have been supported by funding from the NFL charities. As part of this effort, the NFL has supported clinically based research designed to augment the evaluation and management of players with concussion. Neuropsychological testing has increasingly been recognized as a useful diagnostic technology that is used in combination with standard medical care. Numerous research studies have documented the utility of neuropsychological testing in measuring subtle changes in attentional processes, memory and cognitive speed following brain injury (11, 22, 23, 42). Neuropsychological testing provides unique information about changes in cognitive processes that may be missed through sideline or on-field examinations of the athlete and also provides objective information regarding the recovery process during the acute period (13).

There has been a large-scale implementation of neuropsychological testing in colleges (8, 10, 26) and high schools (22, 23, 27); and, numerous studies have examined neuropsychological recovery in high school and collegiate athletes. One published study that examined neuropsychological recovery in NFL athletes (30) suggested that NFL athletes, as a group, made a rapid return to baseline levels of neurocognitive performance following concussion. This finding was in contrast to several studies that found more long-lasting neuropsychological decrements in high school athletes (12, 22, 23, 25). However, none of these studies directly compared professional and younger athletes using the same protocol and an identical neurocognitive test battery. This is the first study that provides a direct comparison of neurocognitive recovery in professional and younger athletes.

This paper describes the implementation of computer based neuropsychological testing in the National Football League from 2000 to 2004. The study directly compares neuropsychological test results in sport-matched samples of high school and NFL athletes, all tested within days of concussions. The paper specifically addresses the following questions: 1) What is the rate of neurocognitive recovery in a sample of NFL athletes? 2) Do professional and high school athletes display similar or different acute recovery following concussions? 3) Is the pattern of neurocognitive impairment and symptom reporting in these two athlete groups similar or different?

The Evolution of Computer-Based Neurocognitive Testing in Professional Football

The use of standardized neuropsychological/neurocognitive assessment protocols in sport is a recent phenomenon and has been discussed in detail elsewhere (23, 30). From 1993 to 2000, traditional "paper and pencil" neuropsychological testing was introduced in the NFL, and it has now been widely adopted in the league. Testing was introduced to provide additional diagnostic information to assist team physicians in making return to play decisions following concussion. This was one part of NFL MTBI Committee's scientific activities, which have been previously described (29–36, 39–41). The Committee has overseen multiple projects in the NFL designed to better understand and manage concussions.

Although the use of traditional neuropsychological testing in the NFL has been found to represent a useful adjunct to the postconcussion evaluation process (20, 30), limitations in the use of paper and pencil testing with athletes became evident. First, traditional testing proved to be limited with regard to its ability to evaluate neurocognitive difficulties following concussion, such as cognitive speed and reaction time. Additionally, neuropsychological consultants who conducted the assessments were limited to the use of less accurate or sophisticated technology (e.g., a stop watch) to assess the reaction-time related parameters. Furthermore, traditional testing proved to be time consuming and logistically difficult to implement for large groups of athletes. For instance, the implementation of preseason baseline testing proved too difficult because preseason team rosters have approximately eighty athletes. It took a team of neuropsychologists days to complete testing.

Computer-based neurocognitive testing was developed to improve player assessment and more accurately measure subtle neurocognitive deficits following mild concussions. Testing typically yields millisecond precision with regard to measurement of reaction time (5, 24). In addition, computer-based testing can be designed to minimize practice effects (e.g., improvement in test performance due to multiple exposures to the test) by randomizing the presentation of stimuli across administrations (22). Finally, computer-based testing can be administered on a computer network with minimal individual supervision and can be administered to groups of twenty or more athletes at a time, thus improving the ability of teams to complete baseline testing in a matter of hours rather than days.

In 2002, the MTBI Committee undertook an extensive internal review of computerized neuropsychological testing. Published literature was reviewed on the subject. Unpublished data was also reviewed with the consent and cooperation of authors of the four major computerized neuropsychological test batteries used in the evaluation of sports-related concussion: Automated Neuropsychological Assessment Metrics (ANAM), CogSport (www-.cogsport.com), Headminders, and ImPact (www.impacttest-.com). We determined that there were adequate reliability data on 1113 subjects and validity data on 1293 subjects. At the conclusion of this review, the Committee determined that there was enough evidence to support the use of computerized neuropsychological testing by NFL teams.

MATERIALS AND METHODS

Data Collection and Analyses

All players participating in the study underwent neuropsychological testing during the 2002 to 2004 seasons. As participation in the neuropsychological study was voluntary, not all NFL athletes with concussion completed neuropsychological testing. Furthermore, not all athletes evaluated postconcussion completed baseline neurocognitive testing prior to injury. Therefore, this study relied on a convenience sample of consecutive injured athletes. For professional and high school groups, only athletes who had completed ImPACT 2.0 or 3.0 were included. NFL and high school athletes who had completed earlier versions of the ImPACT test battery (Versions 1.0) from 2000 to 2002 were excluded from the study due to differences in the make-up of the test battery compared to the current versions.

Baseline Samples

Preseason baseline test data were collected on separate groups of professional and high school football players to form the basis for comparison of postinjury test performance to preinjury levels. *Table 1* shows the characteristics of high school and professional athletes who comprised the baseline samples. There were 68 NFL athletes who made up the baseline sample and 125 high school athletes. For the high school group, athletes were selected for inclusion in the baseline sample if they were male high school football players (ninth through twelfth grade) who had completed baseline testing, The baseline samples of high school and professional athletes were very similar to the postconcussion samples with regard to age, level of education and percentage of athletes in each position group. High school and professional players tested after concussion had a slightly higher mean number of past concussions and were similar with regard to the severity of prior concussions: the history of loss of consciousness was 13% for both groups. Forty percent of the high school sample and 44% of the NFL sample had a history of anterograde

TABLE 1. Sample characteristics of concussed high school and professional football players at first postinjury follow-up (n = 85)[a]

	Professional		High school	
	Baseline	Postinjury 1	Baseline	Postinjury 1
No.	68	48	125	37
Age	24.3 (range = 20–34)	26.3 (range = 20–33)	15.6 (range = 13–18)	15.8 (range = 13–18)
Education	15.8 (range = 14–22)	15.7 (range = 14–22)	9.4 (range = 9–11)	9.6 (range = 6–11)
Prior concussions	0.65 (range = 0–4)	1.2 (range = 0–4)	.59 (range = 0–6)	0.89 (range = 0–3)
Linemen	23 (34%)	12 (25%)	46 (37%)	14 (38%)
Offensive backs	9 (13%)	7 (15%)	37 (29%)	9 (24%)
Defensive backs	28 (41%)	18 (37%)	31 (25%)	11 (30%)
Receivers	6 (9%)	9 (19%)	11 (9%)	3 (8)
Kickers	2 (3%)	2 (4%)	0 (0%)	0 (0%)
LOC	N/A	77% none 13% 1–20 s 2% 21–59 s 6% 1–2 min 2% 3–5 min	N/A	65% none 32% 1–20 s 0% 21–59 s 3% 1–2 min 0% 3–5 min
Retrograde Amnesia	N/A	77% none 2% 1–10 s 2% 11–59 s 0% 1–5 min 2% 6–15 min 17% > 15 min	N/A	49% none 35% 1–10 s 0% 11–59 s 5% 1–5 min 3% 6–15 min 8% > 15 min
Anterograde Amnesia	N/A	80% none 8% 1–5 min 0% 6 15 min 4% 16–30 min 4% 31 min to 3 hr 4%> 3 hr	N/A	49% none 27% 1–5 min 11% 6–15 min 11% 16–30 min 0% 31 min to 3 hr 2% > 3 hr
Disorientation	N/A	29% none 25% 1–59 s 19% 1–5 min 4% 6–15 min 2% 16–30 min 21% > 30 min	N/A	30% none 25% 1–59 s 5% 1–5 min 11% 6–15 min 5% 16–30 min 24% > 30 min

[a] LOC, loss of consciousness; N/A, not available.

amnesia. Nineteen percent of the high school sample and 21% of the NFL sample had a history of an episode of retrograde amnesia. The high school sample did have a higher rate of disorientation than the NFL sample. The average age of the NFL sample was 26.8 years and was similar to the overall league average of 26.5 years (28); and therefore, it is representative of the total population of NFL players with regard to age and experience.

Postconcussion Samples

Table 1 summarizes the sample characteristics. For the purposes of this study, only athletes who completed two postinjury follow-up evaluations were included in the postinjury analyses. Forty eight NFL athletes and 37 high school athletes completed one postinjury evaluation, while 30 NFL and 28 high school athletes completed a second evaluation. Whether an athlete was referred for a second neurocognitive evaluation was determined individually by the team athletic trainer or team physicians. These decisions were clinically based, because athletes who had normal performance following the first evaluation were not evaluated a second time. For the NFL sample, 37% of the athletes returned to play following the initial evaluation and 63% were evaluated a second time within five days of injury. For the high school group, 25%

returned to play prior to the second evaluation and 75% completed the second evaluation. Therefore, NFL and high school athletes who made a rapid recovery did not complete a second evaluation.

Procedures

The NFL neuropsychology program involves the participation of a network of neuropsychological consultants in each NFL city. The network has been described by Pellman et al. (30). For this study, all ImPACT test data was collected by the Director of the NFL neuropsychology program (MRL). It was obtained from team physicians, athletic trainers or team neuropsychologists for entry into a database and subsequent analysis. As the ImPACT battery is computer administered and scored, there were no differences between teams with regard to scoring of the test. Following data collection, the data was stripped of identifying information in compliance with HIPAA standards and stored at the University of Pittsburgh. For the high school sample, data was collected by the University of Pittsburgh Medical Center in cooperation with the high school that the student attended.

Prior to each testing session, the athletes were given a brief explanation of the purpose of neuropsychological testing. Participating players represented a relatively homogeneous group, with the exception of age and level of education. All were males aged 13 to 33 years involved in all offensive and defensive line positions as well as running back, quarterback, and kicking team positions (*Table 1*).

The ImPACT Computer-Based Test Battery

Table 2 shows the individual neuropsychological tests that make up the ImPACT test battery, which evaluates multiple aspects of cognitive functioning and is relatively brief. The battery takes under 30 minutes to administer, is automatically scored and generates a 6 page report. The test battery is heavily oriented towards the evaluation of attentional processes, visual scanning and information processing, although it also evaluates visual memory, verbal memory and visual-motor reactions.

Many studies using the ImPACT have indicated that it is reliable and valid. For example, Iverson et al. (17) found no significant practice effects in a sample of non-injured high school athletes tested twice within several days. With regard to validity studies, ImPACT has been found to correlate with the Symbol Digit Modality test, an often used test of cognitive speed in research with athletes (16, 18). ImPACT also has the capability to discriminating mildly concussed high school athletes (22, 23, 37); and, it has been found to correlate with athlete's self-reporting of neurocognitive decline and "fogginess" (16).

Tests That Comprise ImPACT

ImPACT (version 2.0) consists of six neuropsychological tests, which are designed to target different aspects of cognitive functioning, including attention, memory, processing speed, and reaction time. *Table 2* lists the tests and gives a description of neurocognitive abilities assessed. From the six tests, four separate composite scores were created for verbal memory, visual memory, visuomotor speed and reaction time. In addition, an Impulse control composite score is calculated and provides an assessment of test validity. For this study, all athletes obtained valid baseline testing scores for the NFL and high school groups.

TABLE 2. The ImPACT neuropsychological test battery

Test name	**Neurocognitive domain measured**
Word memory	Verbal recognition memory (learning and retention)
Design memory	Spatial recognition memory (learning and retention)
Xs and Os	Visual working memory and cognitive speed
Symbol match	Memory and visual-motor speed
Color match	Impulse inhibition and visual-motor speed
Three letter memory	Verbal working memory and cognitive speed
Symptom scale	Rating of individual self-reported symptoms
Composite scores	**Contributing scores**
Verbal memory	Word memory (learning and delayed), symbol match, memory score, three letters memory score
Visual memory	Design memory (learning and delayed), Xs and Os (percent correct)
Reaction time	Xs and Os (average counted correct reaction time), symbol match (average weighted reaction time for correct responses), color match (average reaction time for correct response)
Visual motor	Xs and Os (average correct distracters)
Processing speed	Symbol match (average correct responses), three letters (number of correct numbers correctly counted)
Impulse control	Xs and Os (number of incorrect distracters), color match (number of errors)

The Post-Concussion Symptom Scale is also used because it is widely accepted by sports organizations as an accurate identifier of concussion symptoms (2, 20, 21). A 21-symptom checklist asks the injured athlete to rate each possible symptom on a seven-point scale, with zero indicating no experience of a symptom and 6 indicating a severe symptom. This scale is useful because "common" terms are used to describe symptoms and it avoids less common medical terminology (e.g., sensitivity to light is used instead of photophobia; for a review of the Post-Concussion Symptom Scale) (2, 20).

Initial On-Field Diagnosis of Concussion

All NFL teams had a physician and several certified athletic trainers present on the sideline at the time of injury. For high school athletes, concussions were witnessed and diagnosed by physicians and by certified athletic trainers, who were all trained in the diagnosis and management of concussion. In NFL athletes, concussions were diagnosed using standard criteria described previously in articles in this series and used throughout the league (30–34). This involved the identification of a number of neurocognitive (e.g., memory loss) or noncognitive (e.g., headache, nausea, dizziness) criteria identified on the field of play or sideline following a blow to the head. Criteria for high school athletes were highly similar and were based on the presence of mental status changes or player symptoms following a collision or blow to the head. Information regarding the preinjury concussion history was obtained from athletes and their parents. In NFL athletes, concussion history was obtained from the individual teams and medical staff.

Timeline of the Neuropsychological Evaluations

For the high school sample, the initial evaluation was generally conducted two to three days postinjury, as many injuries occurred on Friday nights and the first neurocognitive evaluation was not conducted until the following Monday. For the NFL group, most athletes were evaluated the day after injury, resulting in the completion of the first follow-up evaluation within 24 hours of injury Pellman et al. (30).

With regard to clinical interpretation, NFL players were compared to the normative database for NFL athletes. These data were available to neuropsychologists who served as consultants to the individual teams.

Return to play decisions in the NFL were made by team physicians based on the player's overall clinical evaluations. This included the results of neuropsychological testing and consultations with the team athletic trainers and neuropsychological consultants. Return to play decisions in high school athletes were based on the similar criteria, but decisions were made in consultation with team athletic trainers, the athlete's personal physicians and parents.

Statistics

All statistical analyses were completed using Statistica (38). Descriptive statistics were used to analyze sample characteristics. Z-score transformations were performed to allow comparison across the different composite scores from the ImPACT test battery. Multivariate Analysis of Variance (MANOVA) analyses were conducted to evaluate differences between professional and high school athletes in neuropsychological test results. Because of the different number of subjects evaluated at follow-up 1 and 2, separate MANOVAs were conducted for each of these follow-up periods. Differences between groups on specific indices of the test battery were analyzed with univariate F tests, as part of the MANOVA analyses. Effect sizes (Cohen's d) for differences between NFL and high school groups were calculated by dividing the difference between the postinjury and baseline groups for each sample by the pooled standard deviation (7).

RESULTS

Table 3 shows baseline ImPACT test data, which was gathered to establish average performance or "norms" for NFL (n = 68) and high school football athletes (n = 125). Baseline data came from a sample of athletes from those injured and provides a means of evaluating the postinjury data in the absence of individual baseline values. The preinjury baseline groups provide the basis for comparison if an athlete is injured during the season and also provide the basis for the calcula-

TABLE 3: National football league and high school neurocognitive test performance scores represent raw scores (average and standard deviation in raw score)

	Preseason	Follow-up 1	Follow-up 2
National Football League sample			
Verbal memory	85.7 (9.1)	79.6 (9.6)	84.4 (9.6)
Visual memory	77.3 (13.2)	71.7 (12.7)	77.9 (12.4)
Reaction time	0.58 (0.08)	0.61 (0.09)	0.60 (0.07)
Visual processing	35.5 (5.6)	34.07 (4.4)	35.6 (5.2)
Symptom score	1.34 (2.73)	9.97 (12.2)	6.2 (10.0)
High school sample			
Verbal memory	83.6 (8.2)	76.1 (11.2)	80.5 (12.1)
Visual memory	74.2 (13.2)	63.9 (13.3)	72.1 (11.9)
Reaction time	0.56 (0.07)	0.68 (13.3)	0.61 (0.10)
Visual processing	36.4 (6.3)	31.9 (5.4)	36.3 (6.3)
Symptom score	5.91 (8.65)	25.6 (22)	8.5 (10.1)

tion of Z-scores. Baseline evaluations for NFL and high school athletes were conducted preseason and prior to contact.

Table 3 also shows the mean test scores for postinjury samples for high school and NFL players. All high school athletes included in the postinjury study were initially evaluated within three days of injury (mean = 1.48 d, range = 0-3 d) and all NFL athletes within two days of injury (mean = 1.17 d, range = 1–2 d). For the second follow-up evaluation, the average time postinjury was five days for the high school athletes (range = 2–7 d) and 2.9 days for the NFL group (range = 2-4 d). Therefore, on average, NFL athletes were evaluated sooner postinjury compared to the high school athletes. For our two samples, this difference reflects the fact that NFL athletes routinely undergo neuropsychological testing on Monday or Tuesday following games on Sunday, while high school athletes in our program are most often evaluated on Monday or Tuesday following a game that took place on the previous Friday. As can be seen in *Table 3*, the high school and professional groups demonstrated a decline in raw test scores from baseline.

Table 1 provides demographic information regarding the high school and professional samples. It also presents information regarding on field markers of injury as collected by team medical and athletic training staff. The NFL and high school samples did not differ significantly with regard to loss of consciousness ($\chi^2 = 1.54$, $P = 0.15$) or disorientation ($\chi^2 = 0.00$, $P = 0.955$) following injury. With regard to the presence of retrograde amnesia, the high school sample displayed more amnesia ($\chi^2 = 7.38$, $P = 0.005$). Similarly, the high school group demonstrated greater retrograde amnesia than the professional group ($\chi^2 = 7.40$, $P = 0.007$).

Is There a Difference in Acute Neurocognitive Functioning between Professional and High School Athletes?

Figure 1 presents the results of MANOVA analyses that compare NFL and high school athletes on the four ImPACT composite measures at the first and second follow-up examinations. All scores were converted to standard (Z) scores to facilitate direct comparison using the same metric. Compared to preseason normative performance levels, NFL athletes displayed significantly better ImPACT performance compared to the group of high school football athletes (Wilke's Lambda, F = 4.00, $P < 0.005$). The univariate F tests reveal significant differences between NFL and high schools athletes on the Reaction time (F = 15.8, $P < 0.0001$, d = 0.91) and Processing speed indices (F = 5.29, $P < 0.02$, d = 0.51). NFL athletes performed better on Verbal Memory (F = 3.00. $P = 0.09$, d = 0.39) and the Visual Memory (F = 3.50, $P < 0.06$, d = 0.41) indices but these differences were not statistically significant. Declines in NFL players at follow-up 1 (relative to preseason levels) were not dramatic but did suggest an initial decline in performance on all four composite measures. Performance deficits were mild and generally on the order of 0.25 standard deviation units. In contrast, the high school group displayed significantly larger declines with a decline of almost 0.75 standard deviation on the Verbal Memory composite and a decline (increase in response latency) of 1.53 standard deviation units in reaction time. Less dramatic declines were demonstrated on the Visual Memory and Processing Speed composite scores for the high school sample.

Figure 2 shows the results of a second MANOVA analysis to compare professional and high school athletes at the time of the second follow-up. NFL athletes were evaluated several days sooner than high school players. With regard to an overall comparison of neuropsychological performance in the

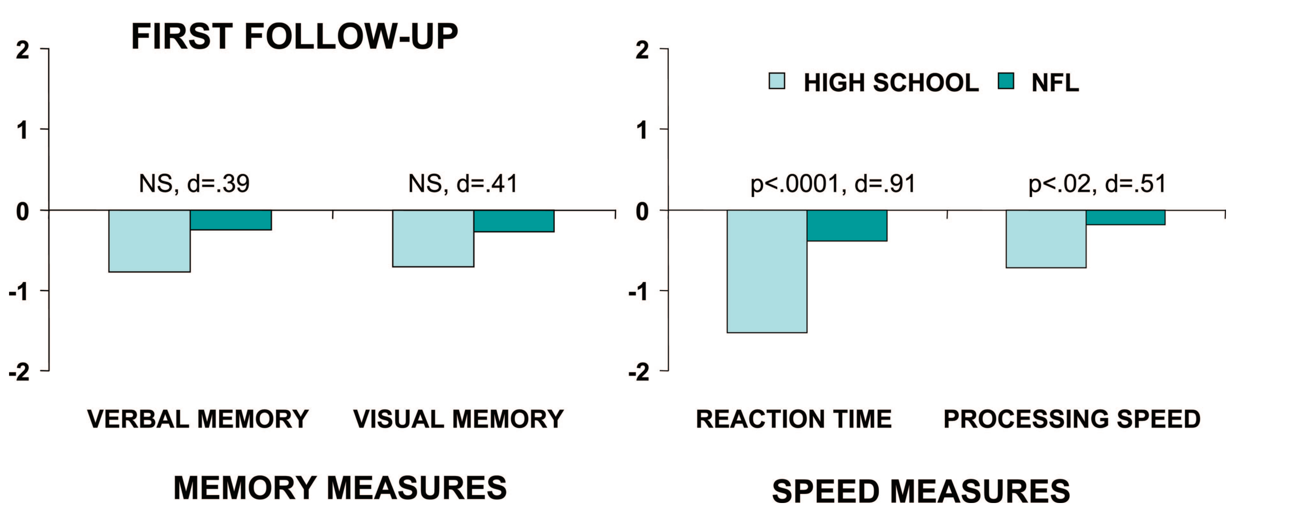

FIGURE 1. *Standard (Z) scores for 37 high school and 48 NFL players tested within five days of injury using ImPACT memory and speed scores at the time of first follow-up. High school athletes were tested within an average of 1.48 days of injury (range = 0–3 d) and NFL athletes within 1.1 day of injury (range = 1–2 d). MANOVA shows differences in performance between NFL and high school athletes on ImPACT composite scores (Wilke's Lambda, F = 4.00, P < 0.005). Univariate differences are represented on graphs.*

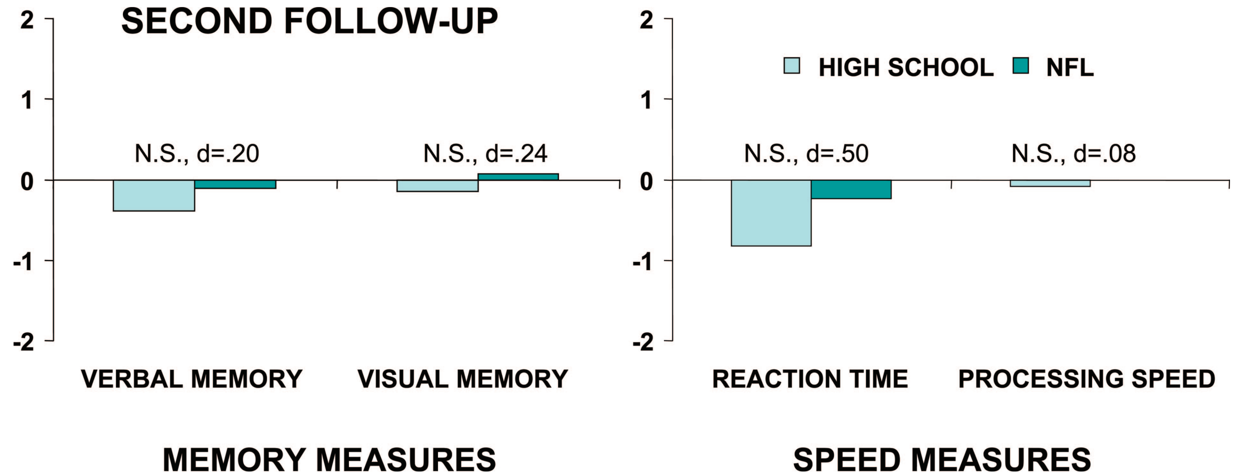

FIGURE 2. *Standard (Z) scores for 28 high school and 30 NFL players, tested within seven days of injury. High school athletes were tested within 5 days of injury (range = 2–7 d). NFL players completed their second evaluation within 2.93 days of injury (range = 2–4 d). MANOVA shows nonsignificant differences in performance between NFL and high school athletes on ImPACT composite scores (Wilke's Lambda, F = 1.09,* P < *0.37). No univariate differences were significant, although there was a trend towards poorer performance in high school athletes.*

NFL and high school groups, the MANOVA was nonsignificant (Wilke's Lambda, F = 1.09, $P < 0.370$). At the second follow-up, approximately three days post injury, the NFL group demonstrated at or above the baseline sample levels on two of the composite indices (Visual Memory and Processing Speed) and very subtle decline on the Verbal Memory and Reaction time composite scores, relative to preseason levels. These standard scores were on the order of one tenth of a standard deviation for Verbal Memory and one fifth of a standard deviation for Reaction Time and are not of any clinical significance. In contrast, the high school group tested within seven days of injury demonstrated poorer performance relative to baseline sample levels. They had a drop of approximately 0.4 standard deviation unit is in Verbal Memory and a 0.83 standard deviation change in Reaction Time relative to preseason performance. There was a smaller decline on the Visual Memory composite and a slight (and not statistically significant) improvement in performance on the Processing Speed index.

The Role of Concussion History

An analysis was undertaken to investigate the potential role of concussion history with regard to neurocognitive recovery in the NFL and high school samples (*Table 1*). Athletes from both samples were classified based on the presence or absence of a concussion history prior to their current injury. Separate MANOVAs were then completed for both samples and yielded nonsignificant results for the NFL (Wilkes Lamda, F = 2.02, $P = 0.109$) and high school (Wilkes Lamda, F = 2.01, $P = 0.115$). Therefore, the presence or absence of a history of concussion was not related to neurocognitive test performance during the first week of recovery. The NFL and high school groups were then assigned to categories based on the absence of concussion history (Group 1), 1 prior concussion (Group 2) or 2 or more concussions (Group 3) to further investigate this issue. A MANOVA was completed with concussion history groups as the independent variable and the four ImPACT composite measures as dependent measures. This analysis did not yield significant results for either the NFL (Wilkes Lamda, F = 1.29, $P = 0.24$) or high school (Wilkes Lamda, F = 1.34, $P = 0.24$) groups.

DISCUSSION

Neuropsychological testing assists team physicians by providing quantitative information on recovery from concussion; and, it has been generally accepted as a component of the medical evaluation following sports-related concussion. More specifically, neuropsychological testing may provide diagnostic information regarding subtle disruptions of cognitive processes such as attention, memory and speed that may not be detected by a cursory sideline evaluation and may not be recognized by the injured athlete. Numerous prior studies have described the neurocognitive recovery of high school (4, 22, 23, 27) and collegiate (8, 9, 21, 26) athletes. These studies have shown neurocognitive recovery within weeks of injury. More recently, a study of NFL athletes found that athletes with MTBI did not perform significantly more poorly on a battery of traditional neuropsychological tests within the first week after injury (30). This study used non-computer based paper and pencil neuropsychological testing and there remains a question that it may have missed subtle cognitive changes in reaction time and cognitive efficiency.

This study represents the first of its kind to use computer-based neuropsychological testing in a group of professional athletes. It was designed to evaluate postinjury neurocognitive functioning in a consecutive sample of NFL and high school athletes who had all completed the ImPACT test battery twice within the first week following their injury. It is the first study to directly compare professional and high school football players using a standardized on-field and postinjury computerized assessment protocol.

Recovery Rates in NFL and High School Athletes

The finding of no significant neurocognitive deficits in the NFL sample within the first week postinjury suggests that NFL athletes with MTBIs recover relatively quickly following injury. This finding supports the only other published study of neuropsychological performance in NFL athletes that did not find significant neuropsychological deficits within one week of injury (30). In contrast, this study found residual difficulties in reaction time and memory in the high school sample and raises the question of differential response to injury in professional and high school football players. There are a number of potential reasons for the apparent difference between professional and high school athletes (30).

First, several researchers have suggested that due to neurodevelopmental factors children are at greater risk of sustaining concussion after head impact. For instance, children are known to exhibit more diffuse and prolonged cerebral swelling after injury than adults (1, 19) and the majority of fatal brain injuries in contact sports have occurred in children younger than 18 (6). There is also evidence from animal research suggesting that the immature brain may be more sensitive to the negative effects of glutamate-mediated N-methyl D-aspartate (NDMA) than in older animal brains. This difference has been hypothesized to play a role in the detrimental effects of excitatory amino acids following brain injury. Finally, a recent clinical study has shown neuropsychological deficits lasting days after injury and a differing rate of recovery depending on the athlete's age (12).

Another hypothesis that may help to explain the differences between NFL and high school athletes is that there may be a different tolerance for concussion in professional and high school athletes. This hypothesis is based on the assumption that NFL athletes represent a highly select group with regard to skill level, size and injury tolerance. The level of conditioning and skill necessary for success in the NFL may result in athletes that are less prone to injury than younger and less talented or well-conditioned individuals. There may be a natural selection process as previously suggested by Pellman et al. (30, 32, 33). Although speculative, this hypothesis is supported indirectly, by current NFL data suggesting that a relative minority of athletes develop postconcussion syndrome (30, 32, 33). In addition, it may be the case that athletes, who have difficulties with concussion during their high school or college years, may choose noncontact sports that have a lower risk of concussion early in their sporting careers. Although this hypothesis is also speculative, it is in line with the observation that most athletes who enter the NFL do not have a significant history of concussion during their high school and college years. For this study, the mean concussion rate was only .65 for the NFL baseline sample (range of 0–4) and 1.2 for the injured NFL group. We also note that in the clinical concussion management program at the University of Pittsburgh Medical Center it is recommended that concussion-prone high school athlete's transition to noncontact sports. In our opinion, it is unlikely that athletes who rise to the level of the NFL are concussion prone.

The NFL and high school samples were not perfectly matched with regard to time of their first and second neuropsychological evaluations, postinjury. Based on when games are played in the NFL (usually on Sunday), most players were evaluated the day after injury. In the high school sample, athletes were more likely to be evaluated several days postinjury based on the fact that most games are played on Friday or Saturday and players do not routinely undergo neuropsychological testing until the following Monday. Since most individuals display neurocognitive deficit immediately following injury, it would be logically expected that the NFL group would demonstrate more dramatic neurocognitive decline since they were being evaluated more quickly after injury. However, this was not the case. In our opinion, this provides additional support for the hypothesis of a quicker recovery in NFL compared to high school athletes.

Relevance to Prior NFL Concussion Studies

In prior papers, the authors have presented the results of clinical evaluations in professional football players after concussion (30–34). However, one paper reviewed neuropsychological test performance using traditional measures (30). The earlier study demonstrated that NFL players, as a group, did not demonstrate neuropsychological deficits on traditional measures and players who sustained multiple concussions did not perform more poorly than those with a single injury. One possible limitation of the earlier study was a reliance on neuropsychological measures that were not specifically developed for sports and did not assess the importance of reaction time and neurocognitive speed. This present paper presents the data using a test battery that has proven to be reliable (17) and valid in detecting subtle changes in reaction time following mild brain injury (22, 23, 37). Therefore, we feel that we have addressed one of the limitations of our prior research.

Regarding the potential cumulative effects of concussion in NFL and high school athletes, this study was designed to evaluate the acute neurocognitive functioning of athletes following concussion. Therefore, we do not purport to present definitive data regarding more long-term outcome in either high school of professional athletes. Hopefully, additional studies will address this issue. However, we did assess the relationship of neuropsychological test results to test performance in our sample. The potential cumulative effect of sports-related concussion remains a controversial issue, and past published studies have differed in their findings (15). Most recently, in a sample of injured NFL athletes who completed traditional neuropsychological testing, Pellman et al. (30) did not find poorer neuropsychological test performance in athletes with a history of three or more concussions. Similarly, the present study did not find a pattern of poorer neuropsychological test scores in a group of NFL athletes who underwent computer-based neuropsychological testing within days of injury. However, it is important to emphasize that the relatively limited sample size in the current study is by no means conclusive. As noted in previous studies, this is a complicated issue and may relate to threshold or age issues (30). This issue will require multiple studies designed to evaluate more long-term markers of outcome in both high school and professional groups. In addition to neuropsychological test results, these studies should involve the evaluation of school performance, activities of daily living and other age-appropriate and relevant measures of real life functioning.

Computer-Based Neuropsychological Testing

The development of the neuropsychological testing program in the NFL has been an incremental process that has involved the ongoing support and coordination of the NFL MTBI Committee. As noted by Pellman et al. (30), the program has evolved to the point where every NFL team is using some form of neurocognitive assessment. Over the past two years, the majority of the league has adopted computer-based neuropsychological testing. This study represents our evaluation of the first two years of data and involves the participation of a subset of eight teams who shared their test data.

Computer based neuropsychological tests have a number of advantages over more traditional testing protocols. One particular advantage is the ease with which athletes can complete baseline testing. This will lead to the completion of baseline testing in the next several seasons. Another advantage is the capability to evaluate subtle changes in reaction time and neurocognitive speed. This capability is highlighted in this present study. The most striking changes in postinjury test performance were evident on the Reaction Time Composite Index. Finally, previous research with computer-based neuropsychological tests has suggested minimal practice effects or improvements in test performance due to prior test exposure (17). This represents a significant improvement compared to more traditional approaches to testing.

The Role of Neuropsychological Testing in Sports

This study highlights the role of neuropsychological testing in professional and high school athletics. Neuropsychological testing represents one of the tools available to assist treating physicians when diagnosing and managing sports-related concussion. Its use is evolving as part of international standards on managing concussion in sports (2). Although a valuable tool, neuropsychological testing should only be used within the context of the clinical medical evaluation and should not be used in and of itself to determine diagnosis or make management decisions such as return to play (30). The overall treatment of the athlete should involve an assessment of the athlete's on-field signs and symptoms, subjective report of symptoms, the observations of the medical staff present at the time of injury, as well as neuropsychological test results. Furthermore, neuropsychological testing can assist in obtaining quantitative information regarding the cognitive status of an athlete that may help to confirm a diagnosis by the team medical staff. Involvement in the testing process also provides reassuring information to injured players and their treating physicians.

Limitations of the Study

As with most research with professional athletics, this research is of an observational nature. As noted in a prior study of NFL athletes, the neuropsychology program was designed to operate with minimum disruption to the NFL teams and athletes, while yielding useful clinical information (30). The study relied on a convenience sample of injured athletes without assurance that the sample is representative of the overall population of injured NFL athletes from 2002 to 2004. However, the sample did match the overall NFL sample in player age and NFL experience.

Currently, all NFL teams are using neuropsychological testing in some form. However, not all teams use the same test battery, conduct preseason baseline testing or use the results in the same manner. We anticipate that future studies of neurocognitive performance in NFL players will allow for the evaluation of larger injury samples and will allow the direct comparison of post injury functioning to individual performance on baseline testing.

Another potential limitation of this study is the lack of established standards for determining abnormal test performance. If preseason baseline testing has been completed on a particular player, abnormal performance was determined by comparing the athletes' postinjury score to their baseline. If the score was poorer than baseline levels, the score was determined to be "abnormal." However, since not all teams who supplied data for this study completed baseline tests, standard scores were calculated as the basis for analysis of deviations from preseason levels of performance. This allowed us to directly compare the athlete to his reference group.

Recently, Reliable Change Index (RCI) scores have evolved to provide an additional determination of abnormal performance (3, 5, 17). RCIs are based on the test-retest reliability of the particular test and they adjust for practice effects. RCIs provide confidence intervals for determining whether or not a test score is reliably different from baseline. However, RCIs have not yet been derived for professional football athletes, although they do exist for high school (3, 17) and Australian rules football athletes (14). As the NFL neuropsychology program develops, the implementation of RCIs should aid in clinical interpretation of neurocognitive recovery following concussion.

REFERENCES

1. Aldrich EF, Eisenberg HM, Saydjaric C, Luerssen TA, Foulkes MA, Jane J, Marshall LF, Marmarou A, Young HF: Diffuse brain swelling in severely head injured children. A report from the NIH traumatic coma bank. **J Neurosurg** 76:450–454, 1992.

2. Aubry M, Cantu RC, Dvorak J, Graf-Baumann T, Johnston K, Kelly J, Lovell MR, McCrory P, Meuwisse W, Schamasch P: Summary and agreement statement of the 1st International conference on concussion in sports, Vienna, 2001. **Clin J Sports Med** 12:6–11, 2002.
3. Barr WB: Neuropsychological testing for the assessment of treatment effects: Methodological issues. **CNS Spectr** 7:300–302, 2002.
4. Barr WB: Neuropsychological testing of high school athletes: Preliminary norms and test-retest indices. **Arch Clin Neuropsychol** 18:91–101, 2003.
5. Bleiberg J, Halpern EL, Reeves D, Daniel C: Future directions for the neuropsychological assessment of sports concussion. **J Head Trauma Rehabil** 13:36–44, 1998.
6. Cantu RC: Second impact syndrome. **Clin Sports Med** 17:37–44, 1998.
7. Cohen J: Statistical power analysis for the behavioral sciences. Hillsdale, Lawrence Earlbaum Associates, 1988, ed 2.
8. Collins MW, Grindel S, Lovell MR, Dede DE, Moser DJ, Phalin BR, Nogle S, Wasik M, Cordry D, Klotz-Daugherty M, Sears SF, Nicolette G, Indelicato P, McKeag D: Relationship between concussion and neuropsychological performance in college football players. **JAMA** 282:964–970, 1999.
9. Collins MW, Iverson GL, Lovell MR, McKeag DB, Norwig J, Maroon J: On-field predictors of neuropsychological and symptom, deficit following sports-related concussion. **Clin J Sports Med** 13:222–229, 2003.
10. Echemendia R, Putukian M, Mackin S, Julian L, Shoss N: Neuropsychological test performance prior to and following sports related mild traumatic brain injury. **Clin J Sports Med** 11:23–31, 2001.
11. Erlanger D, Saliba E, Barth J, Almquist J, Webright W, Freeman J: Monitoring resolution of postconcussion symptoms in athletes: Preliminary results of a web-based neuropsychological test protocol. **J Athl Train** 36:280–287, 2001.
12. Field M, Collins MW, Lovell MR, Maroon J: Does age play a role in recovery from sports-related concussion? A comparison of high school and college athletes. **J Ped** 142:546–553, 2003.
13. Grindel SH, Lovell MR, Collins MW: The assessment of sports-related concussion: The evidence behind neuropsychological testing and management. **Clin J Sports Med** 11:134–143, 2001.
14. Hinton-Bayre A, Geffen GM, Geffen LB, McFarland KA, Friis P: Concussion in contact sports: Reliable change indices of impairment and recovery. **J Clin Exp Neuropsychol** 21:70–86, 1999.
15. Iverson GL, Brooks BL, Lovell MR, Collins MW: No cumulative effects for one or two concussions. **Br J Sports Med** 40:72–75, 2006.
16. Iverson GL, Gaetz M, Lovell MR, Collins MW: Relationship between subjective fogginess and neuropsychological testing following concussion. **J Int Neuropsych Soc** 10:904–906, 2004.
17. Iverson GL, Lovell MR, Collins MW: Interpreting change on ImPACT following sports concussion. **Clin Neuropsychol** 17:460–467, 2003.
18. Iverson GL, Lovell MR, Collins MW: Validity of ImPACT for measuring processing speed following sports-related concussion. **J Clin Exp Neuropsychol** 27:683–689, 2005.
19. Lang DA, Teasdale GM, Macpherson P, Lawrence A: Diffuse brain swelling after head injury more often malignant in adults than children? **J Neurosurg** 80:675–680, 1994.
20. Lovell MR: Evaluation of the professional athlete, in Bailes JE, Lovell MR, Maroon JC (eds): *Sports-Related MTBI*. St. Louis, Quality Medical Publishers, 1999, pp 200–214.
21. Lovell MR, Collins MW: Neuropsychological assessment of the college football player. **J Head Trauma Rehabil** 13:9–26, 1998.
22. Lovell MR, Collins MW, Iverson GL, Field M, Maroon JC, Cantu R, Podell K, Powell JW, Belza M, Fu FH: Recovery from mild MTBI in high school athletes. **J Neurosurg** 98:296–301, 2003.
23. Lovell MR, Collins MW, Iverson GL, Johnston KM, Bradley J: Grade 1 or "ding" concussions in high school athletes. **Am J Sport Med** 32:1–8, 2004.
24. Maroon JC, Lovell MR, Norwig J, Hartl R: Cerebral concussion in athletes: Evaluation and neuropsychological testing. **Neurosurgery** 47:659–672, 2000.
25. McClincy M, Lovell MR, Pardini J, Collins MW: Recovery from concussion in high school athletes. **Brain Inj** (in press).
26. McCrea M, Guskiewicz KM, Marshall SW, Barr W, Randolf C, Cantu RC, Onate JA, Young J, Kelly JP: Acute effects and recovery time following concussion in collegiate football players: The NCAA Concussion Study. **JAMA** 290:2556–2563, 2003.
27. Moser RS, Schatz P: Enduring effects of concussion in youth athletes. **Arch Clin Neuropsychol** 17:91–100, 2002.
28. NFL.com. Current player statistics, Accessed June 2005.
29. Pellman EJ: Background on the National Football League's research on concussion in professional football. **Neurosurgery** 53:797–798, 2003.
30. Pellman EJ, Lovell MR, Viano DC, Casson IR, Tucker A: Concussion in professional football: Neuropsychological testing—Part 6. **Neurosurgery** 57:1290–1293, 2004.
31. Pellman EJ, Powell JW, Viano DC, Casson IR, Tucker AM, Feuer H, Lovell M, Waeckerle JF, Robertson DW: Concussion in professional football: Epidemiological features of game injuries and review of the literature—Part 3. **Neurosurgery** 54:81–97, 2004.
32. Pellman EJ, Viano DC, Casson IR, Arfken CA, Feuer H: Concussion in professional football: Players returning to the same game—Part 7. **Neurosurgery** 56:79–92, 2005.
33. Pellman EJ, Viano DC, Casson IR, Arfken C, Powell J: Concussion in professional football: Injuries involving 7 or more days out—Part 5. **Neurosurgery** 56:1100–1119, 2004.
34. Pellman EJ, Viano DC, Casson IR, Tucker AM, Waeckerle JF, Powell JW, Feuer H: Concussion in professional football: Repeat injuries—Part 4. **Neurosurgery** 55:260–273, 2004.
35. Pellman EJ, Viano DC, Tucker AM, Casson IR, Waeckerle JF: Concussion in professional football: Location and direction of helmet impacts—Part 2. **Neurosurgery** 53:1328–1341, 2003.
36. Pellman EJ, Viano DC, Tucker AM, Casson IR, Waeckerle JF: Concussion in professional football: Reconstruction of game impacts and injuries. **Neurosurgery** 53:799–814, 2003.
37. Schatz P, Pardini JE, Lovell MR, Collins MW, Podell K: Sensitivity and specificity of the ImPACT Test Battery for concussion in athletes. **Arch Clin Neuropsychol** 21:91–99, 2006.
38. Statistica. Statsoft, Inc. Tulsa, 2001.
39. Viano DC, Pellman EJ: Concussion in professional football: Biomechanics of the striking player—Part 8. **Neurosurgery** 56:266–280, 2005.
40. Viano DC, Casson IR, Pellman EJ, Bir CA, Sherman D, Boitano M: Concussion in professional football: Comparison with boxing head impacts—Part 10. **Neurosurgery** 57:1154–1172, 2005.
41. Viano DC, Casson IR, Pellman EJ, Zhang L, King AI, Yang KH: Concussion in professional football: Brain responses by finite element analysis—Part 9. **Neurosurgery** 57:891–916, 2005.
42. Warden DL, Bleiberg J, Cameron KL, Ecklund J, Walter J, Sparling MB, Reeves D, Reynolds KY, Archiero R: Persistent prolongation of simple reaction time in sports concussion. **Neurology** 57:524–526, 2001.

Acknowledgments

This project was undertaken under the auspices of the National Football Leagues (NFL) Committee on Mild Traumatic Brain Injury (MTBI). The Committee is chaired by Dr. Elliot Pellman and includes representatives from the NFL Team Physicians Society, NFL Athletic Trainers Society, NFL equipment managers and scientific experts in the area of traumatic brain injury, biomechanics, basic science research and epidemiology. Authors of this paper are Committee members. With the exception of Dr. Lovell, none of the Committee members has a financial or business relationship posing a conflict of interest to the research conducted on MTBI in professional football. Dr. Lovell has a financial interest in the ImPACT computer based neuropsychological test battery used by many NFL teams. The Committee appreciates the contributions of all of the NFL team neuropsychologists, including Michael Collins, Gary Solomon, Thomas Sullivan, Steven Morgan, Thomas Hardey, Kathy Knee and Don Gerber. The Committee also commends the NFL players, who consented to participate in the study through a blinded identification. The Committee also appreciates the assistance of Cynthia Arfken, Ph.D., from Wayne State Universities, Department of Psychiatry and Behavioral Neurosciences, Center for Healthcare Effectiveness Research, in the statistical analysis of the neuropsychological data. In addition, the efforts of Michael McClincy of Dartmouth College are recognized. Funding for this research was provided by the National Football League and NFL Charities. The Charities are funded by the NFL Player's Association and League. Their support and encouragement to conduct research on MTBI is greatly appreciated.

COMMENTS

The role of neuropsychological testing to evaluate athletes with cerebral concussion has evolved over the past 12 to 15 years. Initially, "paper and pencil" testing was performed. But, it immediately became obvious that this was cumbersome, susceptible to practice learning, and time consuming. Approximately 5 years ago computer-based neuropsychological testing was introduced and was subsequently shown to be accurate, reliable, valid, quick to administer, and highly accepted by high school, college, and professional athletes. It has become a tool that is invaluable in assisting the physician in evaluating and managing an athlete with concussion.

To this end the authors compared neuropsychological test results in high school football players and National Football League (NFL) athletes all tested within days of cerebral concussion. They attempted to determine the rate of neurocognitive recovery, differences in the recovery process particularly as related to a previous history of concussions, and the pattern of impairment and symptoms reported in the two groups.

Their major finding was that NFL athletes had a more rapid recovery than high school athletes and had a rapid return to baseline usually within a few days after injury while high school athletes demonstrated a slower recovery pattern. The reasons for the residual difficulties in reaction time and memory in the high school athlete are speculative. Is the teenager brain really that much more susceptible than the athlete who is in the mid 20s or early 30s? Or, is it really a "natural selection process," as suggested by Pellman et al., with those athletes making it to the professional level being less susceptible to concussive injuries? These questions remain unanswered, but there does seem to be a differential risk of injury in the professional and younger football player.

The author's observation on the relationship of on field markers of injury reassert the now well recognized fact that loss of consciousness is not only not the sine que none of a concussion, but that most concussive injuries now occur without loss of consciousness. Retrograde amnesia at the time of injury seems to be the best on field marker to predict neurocognitive abnormalities. Subsequent demonstration of impaired reaction time on formal neuropsychological testing is another quantitative factor that seems reliable in predicting outcome.

The authors attempted to assess the affective cumulative concussions and increase susceptibility. Although previous studies support this belief, the present study did not reveal poorer performance in the high school athletes who had experienced two or more concussions before their current injury. Because of sample size, definitive statements could not be made by the present authors. With computer-based neuropsychological testing, the axiom "three concussions and you're out" has little use. One severe concussion with prolonged neuropsychological impairment may be sufficient to interdict play, whereas three or more very mild concussions with minimum abnormalities may be acceptable.

Before the introduction of neuropsychological testing, return to play decisions after a cerebral concussion were often subjective, judgmental, and not supported by quantitative data. We think that computerized neuropsychological testing as outlined in this study will become the standard of care to assist physicians with their clinical judgment in assessing and managing athletes with mild traumatic brain injury. As the authors note, all teams in the NFL now use some form of neurocognitivie assessment after concussion injury and 20 out of 32 use the computer-based system, as do approximately 800 colleges and high schools throughout the United States. This will allow much larger studies to be performed, comparing not only high school, but also college athletes, as well as those in the NFL looking at a host of parameters to better evaluate and quantify the affects of mild traumatic brain injury in athletics.

Michael W. Collins
Neuropsychologist
Joseph C. Maroon
Pittsburgh, Pennsylvania

The authors are to be commended for creating widespread implementation of standardized cognitive assessment within professional and high school sports. Standardized cognitive assessment has been difficult to implement within any area of health care, and doing so within professional and high school football is a significant and laudatory accomplishment.

As the authors note, gaining acceptance from sports teams for cognitive assessment involved making such assessment minimally disruptive to the teams' day to day operations. This resulted in numerous compromises, all seeming to be reasonable under the circumstances, but all also introducing deviations to optimal scientific methodology. The authors are to be commended for being explicit regarding many of these limitations, and explicitly labeling their samples as "convenience samples."

The end product, thus, is an ambitious and significant undertaking, impressive in many ways, but based on less than optimal scientific methodology. This is true of many naturalistic studies and is not offered as a criticism. Rather, it is offered as a caution: the methodology of the present study is not sufficient to provide definitive answers to any of the hypotheses. Rather, the present study, as the authors themselves note, contains intriguing findings in need of replication. By being explicit regarding some of the methodological limitations of their study, the authors provide guidance regarding methodologic improvements to be expected of future studies.

The authors frequently note that this is the "first" study of its kind. As such, it is entitled to more methodological leeway than would be tolerable in subsequent studies.

Joseph Bleiberg
Neuropsychologist
Washington, District of Columbia

The authors have provided an initial comparison of concussive induced cognitive sequelae in high school and professional athletes. As this comparison provides novel information, it adds new data to the scientific literature of sports related head injuries. The main concern of this study, and it is a major concern, is that postconcussion test performance was not compared with the athlete's actual baseline. Rather, the authors used a much weaker convenience group design. Therefore, results of this study must be interpreted with significant caution.

Kenneth C. Kutner
Neuropsychologist
Hackensack, New Jersey

This study by Pellman et al. assesses the performance of concussed football players using computer-based neuropsychological tests and symptom inventory assessment compared with a similar, but identical, group and their preseason or baseline testing. This represents the implementation in the NFL of computer-based neuropsychological testing from 2000 and 2004. This study consisted of 68 NFL and 125 high school football players using the ImPACT computerized neuropsychological testing methodology. They found that the NFL players had no significant neurocognitive deficits within the first week after injury. This was in contrast to residual neuropsychological deficits, particularly in reaction time and memory, in the high school population for a similar time course.

There is a good discussion regarding the development and implementation of neuropsychological testing at the NFL level which represents the first report of computer-based neuropsychological testing in professional athletes. They report their findings to help distinguish NFL versus younger athletes and discuss the "natural selection" process, as they have previously proposed. There does seem to be a difference between these particular age groups, and these findings may have bearing upon and should be considered by those caring for both the scholar and professional athletes. Further research will show whether these differences will continue to remain and whether there are inherent distinctions between mild traumatic brain injury occuring in younger age groups versus mature athletes with many years of contact sports experience. The authors are encouraged to continue their research with their unique patient population which should continue to add to our body of knowledge concerning athletic mild traumatic brain injury.

Julian E. Bailes
Morgantown, West Virginia

Three-dimensional rotational angiogram with coil mass depicted in white. After subtraction of the white coil mass, the angiogram shows no evidence of a residual neck. Twelve months after embolization, the wide-necked right superior cerebellar aneurysm remains completely occluded with preservation of the artery. (Feng L, Vinuela F, Murayama Y. Healing of intracranial aneurysms with bioactive coils. ***Neurosurg Clin N Am.*** *2005 Jul;16(3):487–99, v-vi).*