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Sensitivity and Specificity of the Online Version of ImPACT in High School and Collegiate Athletes

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Background: The utility of postconcussion neurocognitive testing versus symptom data has been debated. The sensitivity of the desktop version of the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) tool has been documented, but psychometric properties of the recently released online version of ImPACT have yet to be fully established.

Purpose: To document the sensitivity of the online ImPACT version in samples of (1) symptomatic concussed (high school and collegiate) athletes, and (2) asymptomatic concussed (high school and collegiate) athletes suspected of hiding their concussions.

Study Design: Cohort study; Level of evidence, 3.

Methods: A total of 81 athletes observed to sustain a concussion by a certified athletic trainer or team physician, a finding that was confirmed with reported postconcussion symptoms, completed the ImPACT test within 3 days of injury. Data were compared with an independent sample of 81 athletes who completed preseason baseline cognitive assessments using ImPACT and who were matched (with concussed athletes) on the basis of sex, age, sport, concussion history, and absence of attention deficit hyperactivity disorder and learning disability. An independent group of 37 athletes who were also observed to sustain a concussion completed ImPACT within 3 days of injury. These athletes reported no postconcussion symptoms but were noted for suspected invalid response patterns on ImPACT (Impulse Control index $>$30 and Verbal Memory index $<$69%). The subscale data from the assessments (excluding those contributing to the aforementioned indices) were compared with a matched sample of 37 athletes who completed preseason baseline cognitive assessments in ImPACT (using the same criteria described above).

Results: Data from the ImPACT online version yielded 91.4% sensitivity and 69.1% specificity. For asymptomatic athletes suspected of hiding their concussion, data from ImPACT yielded 94.6% sensitivity and 97.3% specificity.

Conclusion: The online version of the ImPACT tool is a valid measure of neurocognitive performance at the acute stages of concussion, with high levels of sensitivity and specificity, even when athletes appear to be denying postconcussion symptoms.

Keywords: concussion; neurocognitive testing; validity; ImPACT

In the United States, 1.6 to 3.6 million concussions occur annually.[11] The frequency of concussions reported by young athletes has risen dramatically; between 1997 and 2007, the number of youth sports-related concussions seen in emergency rooms more than doubled.[1] Concussion has been declared to be a public health crisis,[17] and there has been a significant increase in concussion-related legislation in recent years. Currently, 38 states have passed youth concussion laws that include a provision requiring all student athletes suspected of a concussion to be cleared by a licensed health care professional before returning to sport.[7] Many of these policies were only recently adopted, and states are currently interpreting the guidelines to implement concussion education and/or management programs.[25]

Over the past 2 decades, diagnostic tools for the management of sports-related concussion have evolved, from paper-based to computer-based measures. Consensus experts in sports concussion have advocated for the use of empirically based measures for the diagnosis and management of concussion, and they have identified neuropsychological testing as a cornerstone of concussion management.[16] The utility of neurocognitive testing for the assessment and management of sports-related concussion was first demonstrated by Barth and colleagues,[2] who recognized the inherent variability in individual performance on neuropsychological measures, which led to a within-subjects comparison to assess for cognitive change after a concussion. Comparing athletes' baseline (ie,

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preseason, preinjury) and postinjury performance allows for detection of relative deficits, as athletes serve as their own controls. This serial assessment model has been widely accepted by researchers and adopted by many, if not most, high school, collegiate, and professional sports programs as an effective measure of evaluating for cognitive impairment.[13,18]

Improper management of concussion can lead to premature clearance for athletic participation, although methods for clear-cut diagnosis and management of concussion remain elusive. Given that the validity of athletes' perceptions of recovery has been questioned because of their tendency to underreport and neglect symptoms,[8,23] return-to-play decisions should not be based primarily on athletes' self-reports of symptoms. Similarly, traditional neuroimaging techniques (eg, magnetic resonance imaging or computed tomography scan) are not sensitive to the acute effects of concussion.[16] As such, combined use of on-field/sideline assessment measures, objective balance testing, symptom checklists, and neuropsychological assessment have been posited to assist in the diagnosis of concussion.[16] The use of neurocognitive testing has been recommended for diagnosis of concussion, but only after postconcussion symptoms resolve.[16] However, this paradigm is contingent on candid reporting of symptoms, and athletes are not always forthcoming with this information.[10] In one study, 53% of varsity high school football players intentionally did not report their concussion to a coach or trainer.[15] Even when athletes report no concussion-related symptoms after a concussion, they may still be experiencing neurocognitive effects. In this regard, 38% of concussed athletes continued to show impaired test performance despite denying the presence of concussion-related symptoms.[4] Finally, relative to normal controls, athletes who denied postconcussion symptoms were found to demonstrate poorer performance on neurocognitive testing.[10]

Conventional paper-based neuropsychological testing poses several limitations for sports medicine practitioners (eg, the extensive time requirements for administration, scoring, and interpretation; practice effects from serial presentation of a finite number of stimuli; and floor and ceiling effects[6]). Computer-based test batteries have been recognized as an effective concussion-screening tool because of their ability to be administered simultaneously to a large group, increased timing accuracy, and decreased practice effects.[6,29] Perhaps the most widely used computerized neurocognitive assessment in North America is the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) tool (ImPACT Applications Inc, Pittsburgh, Pennsylvania), which has been shown to be a reliable[6,22] and valid[9,10,26] means for evaluating sports-related concussion. Originally programmed in FoxBase Pro, and administered on Windows-based computers, the newest version of ImPACT is programmed in Flash and is administered through a web browser. Although the 2 versions are quite similar, the online version employs keyboard input on a choice reaction time task (the *Xs and Os* subtest), instead of mouse-button input from the desktop version. This subtest contributes to the Motor Processing Speed and Impulse Control composite scores on ImPACT. The online version has been shown to yield decreased errors associated with left-right confusion, which in turn, results in fewer invalid results.[27]

To date, research performed exclusively on the online version of ImPACT has been limited to test-retest reliability[9] and incidence of invalid baselines,[26] as compared with the desktop version. The sensitivity (82.5%) and specificity (89.4%) of the desktop version of ImPACT was documented in a sample of concussed and nonconcussed high school athletes,[28] although these findings have been criticized for insufficiently matched groups and inclusion of postconcussion symptom scores in discriminant analyses.[19] The purpose of the current research was to document the sensitivity and specificity of the online version of ImPACT, using carefully matched samples of concussed and nonconcussed athletes, in (1) athletes suspected of sustaining a concussion who reported postconcussion symptoms, and (2) concussed athletes presenting as asymptomatic postconcussion, but suspected of denying concussion-related deficits.

MATERIALS AND METHODS

Data were provided for analysis by the lead programmer at ImPACT Applications Inc, who was blind to the purpose and hypotheses of the study. Institutional Review Board approval was obtained for secondary analysis of deidentified data.

The study extracted baseline and postconcussion ImPACT test data from larger samples of available data. Data were extracted from samples of concussed and nonconcussed athletes in the following manner:

- Symptomatic concussed athletes: Available data of 81 participants were extracted from a sample of 139 concussed athletes. Criteria for inclusion in the concussion group required that participants were concussed athletes aged 13 to 21 years who were tested within 72 hours of sustaining a concussion. Concussed athletes could not have a self-reported history of attention deficit disorder/hyperactivity disorder (ADD/HD) or learning disability (LD), or have a country or language of origin other than the United States/English. All concussed athletes had qualitative data describing the nature of the concussive injury input by a certified athletic trainer or team physician in the "Injury Description" field in ImPACT, and these data were verified by athletes' self-report of concussion-related symptoms at the time of testing. Of note, 3 athletes achieved a score above 30 on the Impulse Control composite, which raised questions regarding the general testing approach taken by those participants. Although outliers on Impulse Control occur in less than 1% of users completing the online version of ImPACT[27] and are typically associated with baseline test performance, these 3 cases were excluded.
- Asymptomatic concussed athletes: Data for a group of 37 asymptomatic concussed athletes were extracted from larger sample of 210 concussed athletes. Criteria for inclusion in the asymptomatic concussion group required that participants were concussed athletes aged 13 to 21 years who were tested within 72 hours of

sustaining a concussion but who reported no postconcussion symptoms (eg, "0" on postconcussion symptom scores). Additionally, these athletes were suspected of invalid response patterns, as identified using preestablished invalidity cutoffs in the Impulse Control (>30) and Verbal Memory (<69%) sections.[26] Other selection criteria were consistent with those described above for symptomatic concussed athletes.

- Nonconcussed athletes: The study extracted available data of 81 and 37 participants from a much larger sample of several thousand normal control (eg, nonconcussed) athletes, stratified by age and provided as part of a normative sample of baseline test data. Criteria for inclusion in the nonconcussed group required that participants were nonconcussed athletes, ages 13 to 21 years, who completed baseline testing at least 6 months after sustaining a recent concussion. Nonconcussed athletes could not have a self-reported history of ADD/HD or LD or have a country or language of origin other than the United States/English. Nonconcussed athletes were matched with concussed athletes on the basis of sex, age, handedness, sport, and history of concussion. Once these data were matched, efforts were made to match concussed and nonconcussed athletes on position played, height, weight, and years of experience playing their sport. No consideration of test scores was made during matching, although athletes with outliers on symptom scores (>3 standard deviations for their respective sex and age) had been removed (by the test developers, as part of a normative process) prior to provision of the files for matching.

Athletes within all samples were included from high schools and colleges from across the United States, as part of ongoing clinical programs implementing baseline and postinjury neuropsychological testing to assist team sports-medicine personnel in making return-to-play decisions after the occurrence of sports-related concussions. Athletes in the symptomatic concussion sample were, by majority, male (67%) and participated primarily in football (44.4%), basketball (20.0%), and soccer (18.5%) (Table 1). As groups were matched on history of concussion, there were no between-groups differences, with no differences noted between male and female athletes (P = .63) (Table 1). Athletes in the asymptomatic concussion sample were also, by majority, male (86%) and participated primarily in football (62.2%), soccer (10.8%), and basketball (8.1%), with no sex differences noted on history of concussion (P = .05) (Table 1).

TABLE 1
Participants' Sport and History of Concussion by Sex

	Males, n (%)	Females, n (%)
Concussed athletes and normal controls (108 males and 54 females)		
Sport		
Football	72 (44.4)	0 (0.0)
Basketball	18 (11.1)	16 (9.9)
Soccer	6 (3.7)	24 (14.8)
Ice Hockey	4 (2.4)	4 (2.5)
Other sports[a]	8 (4.9)	10 (6.1)
Concussion history[b]		
0	34 (21.0)	19 (11.7)
1	50 (30.9)	25 (15.4)
2	14 (8.6)	8 (4.9)
3	10 (6.2)	2 (1.2)
Asymptomatic concussed athletes and normal controls (64 males and 10 females)		
Sport		
Football	46 (62.2)	0 (0.0)
Soccer	6 (8.1)	2 (2.7)
Basketball	4 (5.4)	2 (2.7)
Other sports[c]	8 (10.8)	6 (8.1)
Concussion history[d]		
0	8 (10.8)	5 (6.8)
1	36 (48.6)	4 (5.4)
2	14 (18.9)	1 (1.4)
3	6 (8.1)	0 (0.0)

[a]Other sports = lacrosse, water polo, wrestling (male); cheerleading, softball, volleyball (female).
[b]$\chi^2(3)$=1.74; P = .63 (Bonferroni-corrected α level = .025).
[c]Other sports = ice hockey, lacrosse, wrestling (male); cheerleading, softball, volleyball (female).
[d]$\chi^2(3)$=8.89; P = .05 (Bonferroni-corrected α level = .025).

Procedures

Data were collected at baseline (nonconcussed group) and postconcussion (symptomatic and asymptomatic concussed groups) using ImPACT, during the 2011-2012 athletic season. Individuals with invalid baseline assessments (automatically filtered using preestablished criteria from the test developers[26]) were excluded from the normative sample before its use in this study.

Subscale scores, rather than composite scores, from ImPACT were used in all analyses. The rationale for this method is based on the fact that ImPACT composite scores are summary scores derived by averaging 2 or 3 subscale scores (see Appendix 1, available in the online version of this article at http://ajs.sagepub.com/supplemental/). However, these subscale scores represent a variety of scales and ranges. For example, the Verbal Memory composite is an average of the subscales Word Memory Percent Correct (0%-100%), Symbol Match Total Correct (Hidden) (0-9), and Three Letters Total Letters Correct (0-15). Given that subscales of wider ranges (eg, 0%-100%) would ultimately overshadow between-subjects variance associated with subscales of smaller ranges (eg, 0-9 or 0-12),[30] ImPACT subscale scores were used.

Analyses

We conducted χ^2 analyses to identify between-group differences on sex with respect to history of concussion. A multivariate analysis of variance (MANOVA) was conducted to establish between-group differences on the dependent measures (using the ImPACT subscales). Stepwise discriminant function analysis (DFA) was performed to identify variables that discriminated between concussion groups, with performance on the ImPACT subscale scores

TABLE 2
Classification Table for Symptomatic Concussed Athletes Based on the ImPACT Subscale Scores[a]

Actual	Predicted Group Membership, Concussion Group: Concussed	Control	Total
Positive, n	74	7	81
None, n	25	56	81
Concussed, %	91.4	8.6	100
Not concussed, %	30.9	69.1	100

[a]80.2% of original grouped cases correctly classified. Positive likelihood ratio = 2.95:1; negative likelihood ratio = 0.12:1.

TABLE 3
Classification Table for Asymptomatic Concussed Athletes Based on the ImPACT Subscale Scores[a]

Actual	Predicted Group Membership, Concussion Group: Asymptomatic	Control	Total
Positive, n	36	1	37
None, n	1	36	37
Concussed, %	97.3	2.7	100
Not concussed, %	2.7	97.3	100

[a]97.3% of original grouped cases correctly classified. Positive likelihood ratio = 36:1; negative likelihood ratio = 0.03:1.

as the predictor variables. Canonical discriminant function coefficients (with group centroids) were documented for use in a regression equation. Effect size was reported as either a correlation coefficient or the discriminant analysis for partial η^2 for MANOVA.

RESULTS

Given the nature of the matched samples, groups were equal on demographic variables (eg, age, education, sport, history of concussion, absence of ADHD/ADD/LD).

Symptomatic Concussion Group Versus Normal Controls

A MANOVA was performed with the symptomatic concussion group as the independent variable and the 10 ImPACT subscale scores as the dependent variables. The Hotelling trace coefficient revealed a significant multivariate effect of concussion group on cognitive performance (F[20,302] = 558.6; P = .001; partial η^2 = .97). Subsequent ANOVAs revealed significant effects for all subscale scores (Appendix 2, available online). An additional univariate ANOVA was performed with the concussion group as the independent variable and Total Symptom Scale scores as the dependent variable. Given that concussed athletes were symptomatic, results showed a significant effect of concussion group on concussion-related symptoms (F[1,162]=141.5; P = .001; Partial η^2 = .47).

A discriminant analysis was conducted with scores from the 10 ImPACT subscales, excluding total symptom scores. One significant discriminant function was identified (χ^2[10] = 76.1, P = .001), with 80.2% of cases correctly classified. A total of 91.4% of participants in the concussed group and 69.1% of participants in the nonconcussed group were correctly classified. Means and standard deviations for the variables in the equation are provided in Appendix 2 (available online), and the classification matrix is provided in Table 2. The eigenvalue for these data (.634) suggested that the discriminating power of the function was moderate, with a canonical correlation of .623. The canonical discriminant function coefficients are provided in online Appendix 3, along with group centroids, which allow for use in a regression equation.

Using the classification results of the DFA, the sensitivity of ImPACT subscales (or the probability that a test result will be positive when a concussion is present) is 91.4%. The specificity (the probability that a test result will be negative when a concussion is not present) is 69.1%. The positive likelihood ratio (PLR; the ratio between the probability of a positive test result given the presence of a concussion and the probability of a positive test result given the absence of a concussion) based solely on the ImPACT data is 2.95:1. The negative likelihood ratio (NLR; ratio between the probability of a negative test result given the presence of a concussion and the probability of a negative test result given the absence of concussion) based solely on the ImPACT data is 0.12:1. The positive predictive value (PPV; probability that a concussion is present when the test is positive) based solely on ImPACT data is 91.4%. The negative predictive value (NPV; probability that a concussion is not present when the test is negative) is 69.1%.

Asymptomatic Concussion Group Versus Normal Controls

A MANOVA was performed with the asymptomatic concussion group as the independent variable and the ImPACT subscale scores as the dependent variables (other than those contributing to those contributing to the Impulse Control or Verbal Memory composite scores). The Hotelling trace revealed a significant multivariate effect of asymptomatic concussion group on cognitive performance (F[7,67] = 2048; P = .001; partial η^2 = .99). Univariate ANOVAs revealed significant effects of asymptomatic concussion group on all subscales (Appendix 4, available online).

A discriminant analysis was conducted with the 7 remaining subscale scores from ImPACT, excluding those contributing to Verbal Memory composite (which were used to identify suspected invalid performance). One discriminant function identified the subscale scores as significant factors (χ^2[5] = 93.4, P = .001), with 95.9% of cases correctly classified. Nearly 95% (94.6%) of participants in the asymptomatic concussion group and 97.3% of participants in the nonconcussed group were correctly classified. Means and standard deviations for the variables in the equation are provided in Appendix 4, and the classification matrix is provided in Table 3. The eigenvalue for these data (2.91) suggested that the discriminating power of the function was quite high, with a canonical correlation of .863. The canonical discriminant function coefficients are provided in online Appendix 5.

Using the classification results of the DFA, the combined sensitivity of ImPACT (or the probability that a test result will be positive when a concussion is present) when an athlete is suspected of having sustained a concussion, reports being asymptomatic, and demonstrates an invalid response pattern on ImPACT is 97.3%. The specificity in this situation is 97.3%. The PLR based solely on the ImPACT composite scores is 36:1. The NLR based solely on the ImPACT composite scores is 0.03:1. Overall, the PPV and NPV, based solely on the ImPACT composite scores, are both 97.3%.

DISCUSSION

This study demonstrated the validity of the online ImPACT test during the acute stages of concussion. The ImPACT test scores demonstrated a sensitivity of 91% and a specificity of 69%. Given that diagnosis of acute concussion typically involves the assessment of clinical symptoms,[16] use of ImPACT for assessment of concussion approximates the accuracy of symptom report data, assuming athletes are forthcoming with this information. In this context, the utility of neurocognitive testing while athletes are still symptomatic has been questioned[20,22] and debated in the literature.[12,21,24] Previous researchers have demonstrated that neurocognitive testing provides an additional sensitivity value of 19% over postconcussion symptom data.[31] The current results demonstrate that when athletes are not candid regarding the presence of postconcussion symptoms, specific patterns of performance can identify neurocognitive deficits with 94.6% sensitivity and 97.3% specificity. It is not entirely clear why matched controls concussed were classified (using specificity) with a higher degree of accuracy against athletes suspected of hiding symptoms than against concussed athletes who were forthcoming with symptom report data. Although this aspect was not documented or measured, one explanation may be that athletes attempting to minimize or otherwise hide symptoms may also have engaged in similar cognitive behaviors while taking the ImPACT test, further suppressing their performance. In other words, by attempting to hide symptoms of concussion, or otherwise "look good" on testing, these athletes displayed more variable behavior and paradoxically distinguished themselves from matched controls. In contrast, those athletes who were more forthcoming with symptom data displayed more normal ranges of behavior, thus overlapping more with normal controls, resulting in decreased specificity.

A recent joint position paper listed (among other issues) the need for validation research on computerized neuropsychological assessment devices (CNADs), including construct validity.[3] By demonstrating that the ImPACT test, online version, is capable of measuring the acute effects of concussion, the current research serves to document discriminant validity. Further, the current research answers the call for documentation of a test's sensitivity, specificity, positive predictive value, and negative predictive value. The current literature has documented sensitivity to acute concussion (at 2 days) of 43% and 63%[5] for paper-based measures, with and without symptom data, as well as 23% for paper-based neuropsychological screening measures (with symptoms), and 56% using a more comprehensive neuropsychological test battery.[14] In contrast, computer-based measures have been found to have sensitivity to acute concussion (at 3 days) of 79%[5] to 82%[28] (with symptom data). These data (along with the current results) establish the ImPACT test as a valid means of diagnosing acute concussion, with greater sensitivity to acute effects of concussion than paper-based measures.

The results of this study must be interpreted within the context of its limitations. Although concussed and nonconcussed athletes were carefully matched (eg, on age, sex, sport, history of concussion, absence of ADHD/ADD/LD), this remains a retrospective analysis of data and not a prospective cohort-controlled study. Also, although qualitative observations were made by documented sports medicine professionals, as a means of validating that athletes did, indeed, sustain a concussion, there may have been variability in diagnostic criteria and concussion severity within the sample of concussed athletes. Further, these data represent psychometric properties of the ImPACT test, online version, for only high school and collegiate athletes. As such, these results should not be extended to semiprofessional, professional, or youth athletes. Finally, these results demonstrate the clinical utility of the online ImPACT test for diagnosing acute phases of concussion. Future research may allow for its utility to be extended to later stages of recovery.

Overall, our results show that ImPACT provides postinjury cognitive data that can assist in diagnosis of concussion. Using the neurocognitive data provided by ImPACT, 91% of cases were correctly classified as concussed. When athletes were suspected of hiding concussion-related symptoms and displayed suspicious test-taking behavioral patterns, nearly 95% of cases were correctly classified as concussed. When used appropriately by a trained sports medicine professional, in conjunction with a thorough clinical interview, ImPACT can serve as an effective tool in the concussion management process.

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Appendix 1. Subtests and composite scores for the ImPACT Test Battery

Composite Score	Neurocognitive Domain Measured
Word Memory	Word recognition memory (learning and retention)
Design Memory	Design recognition memory (learning and retention)
X's and O's	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

Composites Score	Contributing Scores/Formula (average of scores presented)
Verbal Memory	Word Memory - total percent correct Symbol Match memory score - Total Correct (hidden)/9 Three letters memory score – Total Sequence Correct/5
Design Memory	Design Memory - total percent correct X's and O's - Total Correct (memory)/12
Reaction Time	X's and O's - average counted correct RT (interference), Symbol Match - average correct RT (visible)/3 Color Match - average correct RT
Motor Processing Speed	X's and O's - total correct (interference)/4 Three Letters - Average Counted Correctly*3
Impulse Control	X's and O's - total errors (interference) Color Match - total errors (commission)

Appendix 2.

Univariate Comparisons for Variables in the MANOVA/Discriminant Analysis.

	Concussion Group			
	Symptomatic Concussed (N=81)	Non-concussed (N=81)		
Variable	*M (SD)*	*M (SD)*	Sig.	Part. Eta^2
Word Memory Total % Correct	81.90 (12.3)	95.3 (5.1)	.0001	.99
Symbol Match Tot Correct (Hidden)	5.99 (1.8)	6.38 (1.9)	.0001	.92
3 Letters Total Letters Correct	12.1 (2.9)	14.2 (1.2)	.0001	.97
Design Memory Total % Correct	70.8 (13.6)	79.0 (13.8)	.0001	.97
X's & O's Total Correct Memory	7.6 (2.8)	8.6 (1.9)	.0001	.92
Symbol Match Average Correct RT	1.7 (.52)	1.5 (.35)	.0001	.93
Color Match Average Correct RT	.84 (.27)	.72 (.13)	.0001	.93
X's & O's Total Correct (Interference)	101.4 (15.3)	113.7 (6.6)	.0001	.99
3 Letter Average Counted Correctly	13.78 (4.4)	16.5 (4.6)	.0001	.92
X's O's Average Correct RT	.60 (.16)	.50 (.05)	.0001	.96
Total Symptom Score	27.9 (18.8)	1.7 (3.0)	.0001	.47

MANOVA (Hotteling's Trace) for Sub-scales: [$F(20,302)=558.6$; $p=.0001$; Partial $Eta^2=.97$]

ANOVA for Total Symptom Score: [$F(1,162)=141.5$; $p=.0001$; Partial $Eta^2=.47$]

Appendix 3.

Canonical Discriminant Function Coefficients and Group Centroids for Symptomatic Concussed Group.

Sub-scale Score	Coefficient	
Word Memory Total % Correct	8.814	
Symbol Match Tot Correct (Hidden)	-.040	
3 Letter Total Letters Correct	.119	
Design Memory Total Percent Correct	-.639	
X's O's Tot Correct Memory	-.106	
Symbol Match Average Correct RT	-.043	
Color Match Average Correct RT	-1.029	
X's and O's Total Correct (Interference)	.012	
3 Letters Average Counted Correctly	-.005	
X's and O's Average Correct RT	-.540	
(Constant)	-7.851	
Group Centroids		
Non-concussed Group		.791
Symptomatic Concussed Group		-.791

Appendix 4.

Univariate Comparisons for Variables in the MANOVA/Discriminant Analysis.

	Concussion Group			
	"Asymptomatic" (N=37)	Non-concussed (N=37)		
Variable	*M (SD)*	*M (SD)*	Sig.	Part. Eta^2
Design Memory Total % Correct	75.9 (13.4)	86.8 (8.8)	.0001	.98
X's & O's Total Correct Memory	66.5 (16.3)	75.0 (11.7)	.0001	.96
Symbol Match Average Correct RT	.680 (.15)	.558 (.07)	.0001	.97
Color Match Average Correct RT	33.1 (7.9)	39.0 (7.4)	.0001	.96
X's & O's Total Correct (Interference)	10.7 (8.5)	6.0 (4.2)	.0001	.63
3 Letters Average Counted Correctly	27.2 (18.8)	1.8 (3.0)	.0001	.67
X's O's Average Correct RT	10.7 (8.5)	6.0 (4.2)	.0001	.63

MANOVA (Hotteling's Trace): [$F(7,67)=2048$; $p=.001$; Partial Eta^2=.99]

Appendix 5.

Canonical Discriminant Function Coefficients and Group Centroids for Asymptomatic Concussed Group.

Sub-scale Score	Coefficient
Design Memory Total Percent Correct	.032
Color Match Average Correct RT	-1.579
X's and O's Total Correct (Interference)	.110
3 Letters Average Counted Correctly	.083
X's and O's Average Correct RT	14.062
(Constant)	-20.605
Group Centroids	
Non-concussed Group	1.669
Concussed Group	-1.669