Effect of (multiple) concussions on information processing speed and working memory in professional ice hockey players

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Abstract

Objective: The present study investigated the effect of concussions on information processing speed and working memory and to what extent the supposed cumulative effects of multiple concussions cause greater cognitive deficits in these domains.

Method: Eighteen ice hockey players were included and separated in three different groups according to the amount of concussions they had suffered from; no concussions, one or two concussions or three or more concussions. The information processing speed and working memory of the athletes were examined by means of the Wechsler Adult Intelligence Scale III (WAIS-III; Wechsler, 1997c).

Results: There is a large effect of concussions on decreased information processing speed and on several areas of working memory.

Discussion and conclusion: Consistent with previous research, it has been established that concussions influence information processing speed. No significant effect of concussions was found on working memory and no significant (cumulative) effects of multiple concussions could be determined. It is assumed that these results appear not to be significant as a consequence of the small sample size.

Content

1 Introduction

After a heading incident during the training last February, a Dutch top league soccer player suffered from black spots before his eyes due to a header. According to a neuropsychologist, these symptoms can indicate a post-commotional syndrome, caused by a brain trauma. Next to that, the neuropsychologist stated that if the player was not treated for his brain trauma, his symptoms would remain for a long while. Furthermore, he declared that it would be best if the soccer player would not play until his symptoms were resolved. The soccer player collected a blow on the head in June 2010 and has since been struggling with the complaints. The neuropsychologist has the impression that both the medical staff of the club as well as the football association misdiagnosed the soccer player, but is convinced that the injury can be treated well. “The complaints should be diagnosed, the player has to receive good coaching and he should not play until he is completely recovered.” ('Demy de Zeeuw moet voorlopig niet spelen', 2011).

Cases like these keep eliciting discussions on the possible risks of concussions that are caused by contact sports and the subsequent policies that should be performed after brain injuries. Therefore, the Dutch Health Council emphasizes that there should be more awareness and adherence to the rules, and that players should be better protected against the inadequate knowledge of the medical staff regarding concussions (Pennarts, 2011).

According to many researchers, concussions sustained during exercise activities or sports such as boxing, football, ice hockey and soccer can lead to significant cognitive impairments (Cantu, 1998; Collins et al. 1999; Guskiewicz et al., 2003; Iverson, Gaetz, Lovell, & Collins, 2004; Iverson, Lovell, & Smith, 2000; Karceski, 2011; Kelly & Rosenberg, 1997; Matser, de Bijl, & Luijtelaar, 1992; Matser, Kessels, Jordan, Lezak, & Troost, 1998; Matser, Kessels, Lezak, Jordan, & Troost, 1999; Matser, Kessels, Lezak, Troost, & Jordan, 2000; Matser, Kessels, Lezak, & Troost, 2001; Thomas et al., 2011). A concussion is a mild traumatic brain injury and is caused by a blow to the head or body, an impact against a hard surface, shaking, or spinning. Concussions occur when the body suddenly stands still causing the brain that floats in the cerebrospinal fluid (CSF) to be jarred against the skull. Concussions cause changes in brain cell functionality and can therefore cause emotional or behavioral changes (Philips, 2007). The American Academy of Neurology (AAN; 1997) describes concussion as “any trauma-induced alteration in mental status that may or may not include a loss of consciousness”. Since loss of consciousness is not an essential factor when diagnosing concussion, it is difficult to assess this ‘state of mind’. There are two types of concussion, as was established on the 2nd International Conference on Concussion in Sport (McCrory et al., 2005). Brain injuries in sports provide an essential opportunity to study the effects of concussions, by investigating athletes who are likely to sustain a concussion. Concussions are very common in some sports and can often be classified in a small number of frequently occurring types of injuries, which provides a practical opportunity to study the effects of brain injuries. We can differentiate simple concussions and complex concussions. A simple concussion can best be described as a concussion that resolves within 7 to 10 days of injury, whereas a complex concussion can be described as a concussion that causes persistent symptoms (McCrory et al., 2005) and can also be defined as post concussion syndrome (PCS; Willer & Leddy, 2006). In most patients with PCS, only a few symptoms occur; headache and fatigue being exposed most frequently. The fatigue is related to alterations in cognitive function, especially when attention and concentration are demanded. Several studies have demonstrated that three or more prior concussions are a significant risk factor for the development of PCS (Phillips, 2007; Willer & Leddy, 2006). Willer and Leddy (2006) suggested that patients suffering from PCS have semipermanent brain injury and thus shift from a diagnosis of concussion to a diagnosis of mild traumatic brain injury (mTBI). It is consequently supposed that the cumulative effects of concussions can lead to enduring deficits such as mTBI.

With the aim of diminishing the amount of cumulative concussions in athletes, Cantu (1992) proposed guidelines and a grading scale for concussions, following his own clinical experience. These guidelines were supplied in order to provide guidance and direction for the sports medicine practitioner in the return-to-play decision (Table 1). These guidelines have been revised by Cantu (2001) to emphasize the duration of posttraumatic symptoms in grading the severity of the concussion and making return to play decisions (Lovell & Pardini, 2010). The guidelines are explained in Table 1.

Table 1. Return-to-play guidelines by Cantu

Guideline	Grade 1	Grade 2	Grade 3
Cantu (1992)	1. No loss of consciousness 2. Posttraumatic amnesia lasts less than 30 minutes	1. Loss of consciousness lasts longer than 5 minutes *or* 2. Posttraumatic amnesia lasts longer than 30 minutes	1. Loss of consciousness lasts longer than 5 minutes *or* 2. Posttraumatic amnesia lasts longer than 24 hours
Cantu (2001)	1. No loss of consciousness *or* 2. Posttraumatic amnesia *or* signs/symptoms last longer than 30 minutes	1. Loss of consciousness lasts less than 1 minute *or* 2. Posttraumatic amnesia lasts longer than 30 minutes but less than 24 hours	1. Loss of consciousness lasts more than 1 minute *or* 2. Posttraumatic amnesia lasts longer than 24 hours *or* 3. Postconcussion signs or symptoms last longer than 7 days

It is suggested that multiple concussions in a short amount of time cause cumulative effects and display more rigorous effects than do first-ever concussions. Cognitive impairments have been found to be even more rigorous and are suggested to cause cumulative effects when a second concussion is attained before the first concussion is resolved (Cantu, 1998; Delaney, Abuzeyad, Correa, & Foxford, 2005; Guskiewicz et al., 2003; Iverson et al., 2004; Karceski, 2011; Kelly & Rosenberg, 1997; Matser et al., 1998; Matser et al. 2001; McCrory et al., 2005; Thériault, De Beaumont, Tremblay, Lassonde, & Jolicoeur, 2011; Willer & Leddy, 2007). The increased risk for further injury could be caused by returning to normal activity before symptom resolution (Cantu, 1998; Delaney et al., 2005; Guskiewicz, 2003; Karceski, 2011; Kelly & Rosenberg, 1997; Thomas et al., 2011). In addition, different authors reported that the risk of suffering from a concussion is four to six times greater in players that have a history of concussion (Cantu, 1998; Colvin et al., 2011; Guskiewicz, 2003; Kelly & Rosenberg, 1997). It was demonstrated that subjects who sustained three or more concussions reported significantly more concussive symptoms (Cantu, 1998; Delaney et al., 2005; Guskiewicz, 2003; Iverson et al., 2004; Phillips, 2007; Willer & Leddy, 2006). The risk of lingering, long-term, or even catastrophic neurological sequelae is significantly increased when returned to play before complete recovery (Delaney et al., 2005; Karceski, 2011; McCrea, Prichep, Powell, Chabot, & Barr, 2010). Therefore, it is important to objectify the level of functioning or recovery before turning back to normal activity levels. The athlete should be fully recovered from a concussion, which means being asymptomatic at rest and with physical exertion, as well as recovery on neuropsychological testing (Delaney et al., 2005). Lovell and Pardini (2010) emphasize the importance of considering the severity of the injury (as measured by duration of loss of consciousness, amnesia and confusion), the athlete’s reported symptoms (e.g. headache, fatigue, photosensitivity), and performance on neuropsychological testing. When returning to play before being completely recovered, an individual risks suffering a second, more severe concussion or even incurring “Second Impact Syndrome” (Delaney et al., 2005). The “Second Impact Syndrome” is considered to be the result of a second concussion that occurs while the athlete is still symptomatic from a previous concussion (Delaney et al., 2005; Kelly & Rosenberg, 1997; McCrea, Hammeke, Olsen, Leo, & Guskiewicz, 2004; Phillips, 2007). Most instances of acknowledged “Second Impact Syndrome” are caused by either a player not reporting an earlier concussion or a reported brain injury that is improperly assessed and managed (McCrea et al., 2004).

The aim of the present study is to investigate whether concussions cause permanent deficits in information processing speed and working memory in athletes with severe concussions. This study will be carried out in order to investigate the cognitive integrity and long-term deficits after concussions in sports. Since partaking in sports is encouraged by health organizations, such as the World Health Organization ("Sport for all" policies encourage physical activity, 2011), it is important to investigate in which way exercise or sports can be as safe as possible and whether safety can be further improved. Although most previous research was mainly aimed at the occurrence of concussions in professional athletes, it is thought that the vast majority of injuries occur at amateur level, and concussions may also occur within the context of recreational activities (Lovell & Pardini, 2010). Previous research suggested that earlier approximations of the amount of concussions that occur are dramatically underestimated (Colvin, et al., 2011; Delaney, Lacroix, Gagne, & Antoniou, 2001; Langlios, Gioia, & Collins, 2007; Lovell & Pardini, 2010; Matser et al. 2001; Matser, Kessels, & Lovell, 2004; McCrea et al., 2004; McCrea et al., 2010; Thomas et al. 2004). This reflects a realistic understanding that prior estimates did not consider the fact that most injuries were previously either unrecognized or not reported to medical or team personnel (Delaney et al., 2001; Lovell & Pardini, 2010; Matser et al. 2001; Matser et al., 2004; McCrea et al., 2004; McCrea et al., 2010; Phillips, 2007; Thomas et al. 2004). The diagnosis of sports-related concussion can be considered complex, since there may be no direct trauma to the head. The athlete may not be aware of the fact that he or she has been injured immediately after the injury (Lovell & Pardini, 2010). This unawareness of the concussion may cause the athlete to continue to play, in that way exposing him- or herself to further injury. Previous research has demonstrated that athletes at all levels of competition may minimize or hide symptoms in an attempt to prevent their removal from the game, thus creating the potential for exacerbation of their injury, which makes this situation even more complicated (Cantu, 1998; Lovell et al., 2002; Thomas et al., 2011). It is thus of major importance to investigate the effect of concussions on cognitive functioning and to make athletes at all levels aware of the consequences of returning to play before resolving the symptoms. Therefore, it should be investigated whether permanent consequences are preventable and whether athletes should be protected against themselves. The brain is one of the most important organs in the human body for quality of life, since it regulates and integrates a great variety of endocrine, autonomic and behavioral processes that are essential for the survival and reproduction of the organism (Janardhan & Bakshi, 2000; Mowry et al., 2009). Therefore, it is of high importance to ensure that the brain is not to be damaged. We will investigate the effect of brain concussions in ice hockey players, since ice hockey seems to be one of the sports with the highest risk in obtaining brain concussions (Cantu, 1998; Delaney, 2004; Delaney & Frankovich, 2005; Delaney et al., 2005; McCrea et al., 2010). Therefore, the main aim of this study is to examine the influence of concussions on long-term deficits in information processing speed and working memory in advanced ice hockey players.

Many studies have focused on investigating concussions caused by physical exercise and sporting activities in which brain injuries often occur (Cantu, 1998; Collins et al. 1999; Delaney, Puni, & Rouah, 2006; Guskiewicz et al., 2003; Iverson et al., 2004; Karceski, 2011; Kelly & Rosenberg, 1997; Matser et al., 1992; Matser et al., 1998; Matser et al., 1999; Matser et al., 2000; Matser et al., 2001; Thériault et al., 2011; Thomas et al., 2011). The cognitive effects of concussion can be best determined by means of neuropsychological methods (AAN, 1997; Cantu et al., 1998; Iverson et al., 2000, 2004; Karceski, 2001; Kelly & Rosenberg, 1997; Thériault et al., 2011; Willer & Leddy, 2006). By carrying out this study, more knowledge on the role of brain concussions will be obtained, which makes it possible to look for future solutions in order to prevent or minimize the chance of brain concussions. Since the possible risks of concussion that often occur in contact sports keep eliciting discussions, it is important to investigate the long-term effects of concussions. This importance of increasing knowledge in risks and policies that should be performed after brain injuries is also emphasized by the Dutch Health Council (Pennarts, 2011). Prior research has shown that the most serious brain injuries would occur in ice hockey (Karceski, 2011; Kelly & Rosenberg, 1997). However, to our knowledge, no previous research has examined long-term effects and permanent consequences caused by concussions in ice hockey players using neuropsychological testing by means of the Wechsler Adult Intelligence Scale III (WAIS-III; Wechsler, 1997c), that focuses on information processing speed and working memory. Therefore, the present research will focus on the differential cognitive performance of concussed vs. non-concussed athletes on information processing speed and working memory in ice hockey players by means of neuropsychological testing using subtests of the WAIS-III. These differences, plausible long-term deficits caused by concussions, will be examined by means of the following assumptions.

It is hypothesized that concussions lead to decreased information processing speed and reduced working memory.

Furthermore, we expect that multiple concussions have a greater negative influence on the extent of cognitive deficits.

2 Methods

2.1 Population

Subjects in the present study were 19 members of a top league ice hockey team playing in the Swiss national league.

2.2 Procedure

The participants were contacted via the coach of the team. After consent of the team coach, the participants were individually asked to give informed consent to participate. Subsequently, the following self-reported data were collected by means of a comprehensive interview: age, playing position, years of participating in ice hockey (nonprofessional and professional), history of concussion (sports and non-sports related) including the number of concussions and whether these concussions contained loss of consciousness. All participants were interviewed and examined using subtests from the WAIS-III (Wechsler, 1997c). One participant was excluded because of insufficient understanding of the English language. The testing procedure was in KopfwehZentrum Hirslanden in Zürich and was about 30 minutes per participant, which included both the short interview as well as the neuropsychological testing, using the subtests Symbol Search, Digit Symbol, Digit-Letter Recall, Arithmetic and Digit Span of the WAIS-III.

2.3 Tests

In order to obtain a clear insight into the abilities of visual speed processing and working memory relative to the amount of previous brain concussions, five subtests of the WAIS-III were used and a short questionnaire was taken. The subtests of the WAIS-III that were used, are Symbol Search, Digit Symbol, Digit-Letter Recall, Arithmetic and Digit Span. Symbol Search and Digit Symbol are used to measure the Processing Speed Index (PSI), whereas Digit-Letter Recall, Arithmetic and Digit Span determine the Working Memory Index (WMI).

2.3.1 Symbol Search

Symbol Search comprises a series of paired groups, each pair consisting of a target group and a search group. The subject’s task is to decide whether either of the target symbols is in the search group, a group consisting of five search symbols. This subtests measures the processing speed and attention (Tulsky, Saklofske, & Zhu, 2003).

2.3.2 Digit Symbol

Digit Symbol consists of rows containing small blank squares, each paired with a randomly assigned number from one to nine. Above these rows is a printed key that pairs each number with a different nonsense symbol. The subject must fill in the blank spaces with the symbol that is paired to the number above the blank space for 120 sec. Digit Symbol is a test of psychomotor performance that is relatively unaffected by intellectual prowess, memory or learning (Lezak, 2004).

2.3.3 Digit-Letter Recall

In Digit-Letter Recall, subjects hear lists of randomized numbers and letters (in alternating order) of increasing lengths. Subjects are asked to repeat digits and letters from the lowest in each series, and digits always first. This subtest quantifies auditory recall and attentional deficits (Lezak, 2004).

2.3.4 Arithmetic

Arithmetic consists of arithmetic problems presented in story format arranged according to level of difficulty. This test has one of the highest correlations with working memory of all the WAIS-III tests and indicates deficits in immediate memory, concentration, or conceptual manipulation and tracking (Lezak, 2004).

2.3.5 Digit Span

Digit Span comprises two different tests, Digits Forward and Digits Backward, which both consist of seven pairs of random number sequences that the examiner reads aloud at the rate of one per second. The subject's task is to repeat the sequence respectively exactly as it is given or in exactly reversed order. Both subtests thus involve auditory attention and depend on a short-term retention capacity (Lezak, 2004).

The WAIS-III provides a very accurate representation of a person's intelligence, on two different IQ-scales: a verbal IQ and a performance IQ (Wechsler, 1997c). The WAIS-III has been demonstrated to have high validity and reliability, and small standard errors of measurement (Ryan & Ward, 1999).

2.4 Data analysis

In order to examine the effects of concussions, between-group analyses were carried out. To evaluate the relationship between concussions and visual speed processing and working memory, an independent samples test was carried out to examine whether the concussed and the non-concussed group have the same mean. PSI and WMI were acquired by adding the standardized scores on the PSI and WMI subtests as explained in the WAIS-III manual. PSI and WMI percentile scores were used to evaluate the plausible damaged brain or higher level of brain functioning of the participants and were obtained by adding the results on the subtests and subsequently comparing these to the WAIS-III norm group, in which this percentile score logically represented the percentage of people scoring lower than or equal to the subject. Percentile scores were used in order to obtain a clear insight in the level of PSI and WMI of the subjects compared to the WAIS-III reference scores. For further specification on the results on the PSI and WMI, an independent samples test was completed with the Symbol Searching, Digit Symbol, Digit-Letter Recall, Arithmetic and Digit Span being entered as the dependent variables; concussion (yes or no) was the independent variable.

Since there were insufficient participants suffering three or more concussions to conduct statistical analyses over these data, the effect of multiple concussions on information processing speed and working memory was studied by means of generating scatterplots for all WAIS-III subtests. The amount of concussions an athlete had suffered from was set as the x-variable and the scores on the subtests were represented on the y-axis.

Statistical significance was set at $\alpha = .05$ and the reported *t*-values were calculated by dividing the mean of differences by the standard error of differences. Furthermore, the effect size was calculated by dividing the difference between two means by the standard deviation.

Statistics were performed using SPSS 17.0 (SPSS Inc., Chicago, IL).

2.5 Ethical issues

Participants were well informed about the content of the study and the tests that would be conducted. The participants were informed about the timeframe of the interview and testing procedure by means of a short introduction by the experimenter. The experimenter also informed the participants about guaranteeing of their privacy after the experiment. None of the participants refrained from testing during the testing phase and all the participants gave consent to use their scores in the present study.

3 Results

Eighteen athletes were identified for participation. Seven (38.9%) athletes had no history of concussion, whereas eleven (61.1%) athletes had sustained at least one concussion. Of these 11, eight (72.7%) athletes had sustained one or two concussions and three (27.3%) athletes had a history of three or more concussions.

Table 2. Descriptive statistics for non-concussed vs. concussed athletes

		Non-concussed athletes (n = 7)	**Concussed athletes (n = 11)**	***t*-value**	***p*-value**
Age		28.3 ± 3.2	24.4 ± 4.2		
Years participating in ice hockey		22.9 ± 4.5	19.6 ± 5.0		
Years participating in professional ice hockey		9.9 ± 2.2	7.1 ± 4.7		
Processing Speed Index	**Symbol Searching**	13.9 ± 1.1*	11.4 ± 0.8*	1.97	.03
	C-score (min-max)	C = (10-18)	C = (7-15)		
	Digit Symbol	10.4 ± 0.7	9.1 ± 0.7	1.30	.11
	C-score (min-max)	C = (8-13)	C = (5-14)		
Working Memory Index	**Digit-Letter Recall**	13.7 ± 1.1*	11.6 ± 0.5*	2.00	.03
	C-score (min-max)	C = (8-18)	C = (9-14)		
	Arithmetic	11.7 ± 0.6*	9.9 ± 0.7*	1.83	.04
	C-score (min-max)	C = (10-14)	C = (5-13)		
	Digit Span	11.6 ± 1.5	11.6 ± 0.6	-.05	.48
	C-score (min-max)	C = (4-15)	C = (9-15)		

The primary outcome measures in this study were WMI and PSI, representing respectively the working memory and processing speed. Since the Kolmogorov-Smirnov test showed that the scores on all five subtests were normally distributed and Levene's test demonstrated that the data were not significantly skewed or kurtosed, independent samples tests were carried out. For each hypothesis a direction was set, therefore 1-tailed testing was performed. Only two athletes scored below the 20^{th} percentile of PSI, whereas six athletes scored above the 80^{th} percentile. On WMI, the results are all the more excellent, with only one athlete scoring below the 20^{th} percentile and even eight athletes scoring above the 80^{th} percentile. This indicates that the participants, both the concussed as well as the non-concussed athletes, have a highly developed processing speed and working memory, compared to norm groups.

Independent samples *t*-tests were performed for both PSI subtests to investigate whether information processing speed in non-concussed and concussed athletes was affected by one of the subtests. The results indicated that non-concussed athletes scored significantly higher than concussed athletes in the subtest Symbol Search, showing a medium to large effect size of concussions (*d* = .44). Non-concussed athletes did not score significantly higher on the Digit Symbol subtest than concussed athletes. An independent samples test was also carried out for all three WMI subtests to investigate whether working memory in non-concussed and concussed athletes was affected by the scores on the subtests. Results on WMI subtests showed that non-concussed athletes scored significantly higher than concussed athletes on Digit-Letter Recall and on Arithmetic, showing a medium to large effect size of concussions on both Digit-Letter Recall and Arithmetic (respectively *d* = .44 and *d* = .41). However, there appeared to be no significant difference between non-concussed athletes and concussed athletes on Digit Span (Table 2).

Figure 1 shows the results of all five subtests, demonstrating that there is a significant effect of concussion on PSI subtest Symbol Search and on WMI subtests Digit-Letter Recall and Arithmetic (see also; Table 2).

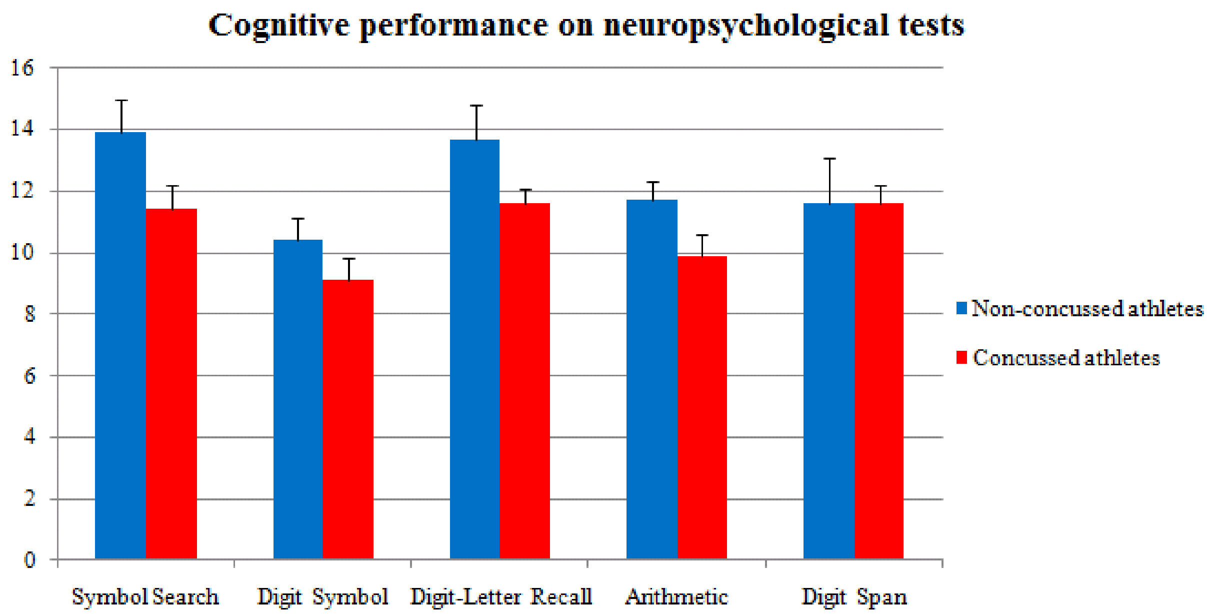

Figure 1. Mean standardized scores and standard error of the mean (SEM) on WAIS-III subtests. Y-axis represents c-scores on WAIS-III subtests; X-axis represents WAIS-III subtests.

The effect of multiple brain concussions on information processing speed and working memory could not be statistically investigated because of the small sample size of the three groups, specifically the group with three or more concussions appeared to contain insufficient participants. Therefore, the scores on PSI and WMI subtests have been studied by means of scatterplots for all subtests that represent the results of each participant separately (see Appendix 2). Results on information processing speed subtests Symbol Search and Digit Symbol imply that non-concussed athletes in general scored higher than athletes suffering one concussion. Additionally, both non-concussed athletes as well as athletes suffering one previous concussion appeared to score higher than athletes suffering two concussions in both PSI subtests. However, it appeared that athletes with three or more concussions in the subtests Symbol Search and Digit Symbol did not follow this course and did not appear to score significantly lower than non-concussed athletes or athletes suffering one or two concussions (see Appendix 2).

To examine whether the results on working memory were affected by the amount of concussions, scatterplots were also created for all three WMI subtests. The results on all three WMI subtests again indicated that non-concussed athletes scored higher than athletes suffering one and two concussions, athletes suffering one concussion also scored higher in general than athletes with a history of two concussions. However, once again, athletes with three or more concussions appeared not to score lower than athletes suffering two previous concussions on subtests Digit-Letter Recall and Digit Span. On WMI subtest Arithmetic, concussions appeared to have a cumulative effect, with athletes suffering more concussions showing lower scores (see Appendix 2). It appeared that non-concussed athletes score higher on average on all five WAIS-III subtests than do athletes suffering one or two concussions. Athletes suffering one concussion also appeared to perform better on average than athletes with a history of two concussions. Athletes with a history of three or more concussions, however, do not score remarkably lower than non-concussed athletes on the majority of WAIS-III subtests.

4 Discussion

The aim of the present study was to investigate whether concussions had any effect on the cognitive domains information processing speed and working memory. It was hypothesized that concussions cause a decrease in information processing speed and reduce the working memory. Furthermore, it was hypothesized that multiple concussions cause additional negative effects on the extent of cognitive deficits.

Results of the present study indicate that experiencing a concussion has a significant effect on the information processing speed but appeared not to have a significant influence on working memory, although it had a significant effect on several areas of working memory. Next to that, multiple concussions did not appear to have a greater effect on cognitive deterioration.

4.1 Effect of concussions on information processing speed

The main finding in our study was that the presence of concussions was associated with a decreased information processing speed (see Table 2). With these results, we could confirm the hypothesis that concussions lead to decreased information processing speed. Athletes with no history of concussion showed a higher PSI than athletes who suffered from a concussion. To investigate whether this difference was caused by a large difference in any of the subtests that were performed to obtain a total PSI score, an independent samples test was performed. The independent samples t-test (one-tailed) results for the Symbol Search task showed significant differences between concussed and non-concussed athletes, representing a medium to large effect size. The difference between concussed and non-concussed athletes appeared not to be significant for the Digit Symbol subtest. This implies that PSI is influenced by the presence of concussions, meaning that concussions have a great effect on information processing speed.

These results are in accordance with previous research in which it was stated that concussions have an effect on information processing speed. Collins et al. (1999) found that a history of concussion was significantly and independently associated with long-term deficits in speed of information processing. Matser and colleagues (2001) suggested that concussions play a fundamental role in the development of cognitive impairment, since an increasing number of concussions was related to a significant decline in visuoperceptual processing. By showing that there is a significant effect of concussions on information speed processing, the present study is therefore in accordance with results from previous research. Although it has been supposed that the most serious brain injuries would occur in ice hockey, up till now, no earlier research assessed the effect of concussions in ice hockey players by means of the WAIS-III (Karceski, 2011; Kelly & Rosenberg, 1997).

4.2 Effect of concussions on working memory

We found that concussions did not significantly reduce all areas of WMI (see Table 2). Athletes with no history of concussion did not score significantly higher on WMI than athletes who suffered from a concussion. As well as in the PSI scores, we conducted an independent samples test to investigate whether this non-significance was caused by one of the subtests. The independent samples t-test (one-tailed) results for the Digit-Letter Recall task showed that non-concussed athletes scored significantly higher than concussed athletes, representing a medium to large effect size. A significant effect of concussions was also found on Arithmetic, showing a medium to large effect size. The difference between concussed and non-concussed athletes, however, appeared not to be significant for the Digit Span subtest (see Table 2). We can thus conclude that there is a definite effect of concussions on several areas of working memory.

With these results, our expectation that concussions lead to reduced performance on all areas of working memory could not be confirmed. Past studies contradict these results concerning the effect of concussions on working memory, suggesting that concussions have a definite effect on working memory. Matser et al. (1998) found that an increasing number of concussions was related to poorer performance on memory, planning and visuoperceptual performance. Other studies of Matser et al. (1999) revealed that concussions might play a fundamental role in cognitive impairment and showed that concussions were significantly related with reduced performance on memory tests. In a recent study of Thériault et al. (2011), the authors stated that athletes with a history of concussions had an affected working memory storage capacity. Moreover, it appeared that the amount of previous concussions was correlated with reduced working memory storage. Collins et al. (1999) also showed that a history of concussion is significantly and independently associated with long-term deficits in the domains of executive functioning, as well as an increase in self-reported symptoms. It appeared that these defects are particularly present in individuals who have sustained at least 2 concussions (Collins et al., 1999). The results in the present study appear to be caused by the inferior divergence of the performance of concussed and non-concussed athletes on a specific subtest. It could, however, also be a result of the small sample size, which increases the chance on potential divergence and therefore enhances the chance on outliers. The results of one particular case can significantly affect the results in a study with such a small sample size. This is also confirmed in the present research, since it has been demonstrated that one of the three athletes suffering from three or more concussions has performed so exceptionally high on the WAIS-III subtests, which caused the mean of this group to increase remarkably.

4.3 Effect of multiple concussions

The effect of multiple concussions that was hypothesized to cause inferior performance, could not be confirmed in the present study. The effect of multiple concussions on information processing speed and working memory was studied by means of a scatterplot that showed the performance of each participant on the subtests. These performances on the WAIS-III subtests were represented according to the athletes' history of concussions, to obtain a clear view on the average performance relatively to the amount of concussions. On information processing speed, the non-concussed group scored higher than the athletes suffering one or two concussions, but did not differ from athletes with three or more concussions. There appeared to be no significant difference either on information processing speed between both groups suffering from previous concussions. (see Appendix 2). Results on information processing speed subtests indicate that non-concussed athletes in general scored higher than athletes suffering one concussion. Furthermore, both non-concussed athletes as well as athletes suffering one previous concussion appeared to score higher than athletes suffering two concussions in both PSI subtests. However, athletes with three or more concussions in the subtests Symbol Search and Digit Symbol appeared not to score lower than the average non-concussed athlete or athletes suffering one or two concussions (see Appendix 2). These results were unexpected, but because of the small sample size and consequently the little power of the research, these suppositions of unaffected information processing speed in athletes with multiple concussions cannot be affirmed.

The results on WMI subtests also indicated that non-concussed athletes scored higher than athletes suffering one and two concussions, and athletes suffering one concussion scored higher in general than athletes with a history of two concussions as well. However, athletes suffering three or more concussions again appeared not to score lower than athletes suffering two previous concussions on WMI subtests Digit-Letter Recall and Digit Span. On Arithmetic, there appeared to be a cumulative effect of concussions, with athletes suffering more concussions showing lower scores (see Appendix 2). Non-concussed athletes scored higher on average on WAIS-III subtests than athletes with a history of one or two concussions. Athletes suffering one concussion also appeared to perform better on average than athletes with a history of two concussions. These observations imply that there is a cumulative effect of concussions, since the performance on WAIS-III subtests decreases with each additional concussion. Athletes with a history of three or more concussions, however, do not score remarkably lower than non-concussed athletes on the majority of WAIS-III subtests. This suggests that multiple concussions do not cause more severe cognitive deficits in terms of affected information processing speed and working memory than do single or secondary concussions. Since it has been proposed that multiple concussions have a cumulative effect on the severity of symptoms and decline in cognitive performance, this result is unexpected. These observations do not support our hypothesis that multiple concussions have a greater negative influence on the extent of cognitive deficits, but because of the insufficient power of the study, these suppositions cannot reject the hypothesis.

Our observations are in accordance with research by Macciocchi, Barth, Littlefield and Cantu (2001) in which it was reported that there are no statistical differences observed on neuropsychological tests in athletes suffering from either one or two concussions. However, similar to our study, the samples sizes in this research were very small.

McCrea et al. (2010) recommended that there should be implications for injury prevention policies, particularly regarding prevention of recurrent concussion and the risks of possible catastrophic outcome in sports. A study by Phillips (2007) stated that players who had suffered from three or more concussions were five times more likely to report mild cognitive impairment. Previous research by Guskiewicz et al. (2003) also showed incompatible results by suggesting that a history of concussions is associated with slower recovery of neurological functioning following multiple concussions and that these previous brain injuries are associated with an enlarged risk of future concussions. Furthermore, Guskiewicz et al. (2003) suggested that there might be a 7- to 10-day window of increased susceptibility for recurrent concussive injury. These statements are also in accordance with previous studies of Cantu (1998), who supposed that the ability to process new information was decreased after a minor head injury. Next to that, they showed that the severity and duration of functional impairment was larger with repetitive concussions. With these results, the authors suggested that the effects of concussions were cumulative (Cantu, 1998). In addition to the findings of Cantu, Thériault et al. (2011) found that athletes with a history of three or more concussions exhibited significantly reduced working memory and decreased processing speed relative to both concussed athletes with only one or two prior concussions and athletes without concussions. Consequently, it was stated that working memory storage was further decreased with subsequent concussions (Thériault et al., 2011). Concussions appeared to be significantly and independently associated with long-term deficits in executive functioning and information processing speed (Collins et al., 1999; Delaney et al., 2001; Iverson et al., 2004; McCrea et al., 2010). These defects appear to be present in individuals who have a history of multiple concussions (Collins et al., 1999; Iverson et al., 2004). Collins et al. (1999) showed that a history of a single concussion does not appear to result in the long-term cognitive deficits that are associated with multiple concussions. These findings are consolidated by Iverson et al. (2004), who demonstrated that athletes with multiple concussions showed worse on-field severity markers associated with their next concussion relatively to athletes who experienced their first concussion. Athletes with a history of multiple concussions appeared to be eight times more likely to experience 5 or more minutes of mental status disturbance and had more adverse consequences in the acute recovery period from a subsequent concussion (Iverson et al., 2004). Moreover, McCrea et al. (2010) suggested that this lingering cerebral dysfunction lasted beyond the observed clinical recovery period. These findings add increased empirical support to the concept of a “window of cerebral vulnerability,” during which the brain has not yet returned to a normal state of metabolic and cerebral functioning (McCrea et al., 2010), such as Second Impact Syndrome or Post-Concussion Syndrome (Delaney et al., 2005; Kelly & Rosenberg, 1997; McCrea et al., 2004; Phillips, 2007; Willer & Leddy, 2006).

The goal in this study was to examine the long-term effects of concussions on information processing speed and working memory in ice hockey players. We have found significant effects of concussions on information processing speed as well as on several areas of working memory. These findings are important in obtaining more knowledge in cognitive integrity after concussions and the long-term deficits and lasting effects of severe brain injuries, making it possible to look at ways of reducing the chance on concussions. Since the effects of repetitive concussions have been demonstrated to cause dementia pugilistica, a neurologic disorder that primarily affects athletes who are exposed to multiple head injuries, such as in boxing, soccer, football, ice hockey, and the martial arts (Rabadi & Jordan, 2001), it is of great importance to increase knowledge on the lasting effects of concussions (Bazarian, Cernak, Noble-Haeusslein, Potolicchio, & Temkin, 2009). Previous research in elite athletes has demonstrated that clinical symptoms of dementia pugilistica often occur 10 to 20 years after retirement from the sport and are associated with declines in mental and physical abilities, such as dementia and parkinsonism (Bazarian et al., 2009). It is therefore important to reduce the probability on this type of early dementia by investigating the lasting effects of concussions.

4.4 Limitations

In the present study, a small sample size of athletes with multiple concussions was used. This could have limited the ability to detect correlations between the amount of concussions and its effect on cognitive functioning. When dividing this small sample size into three groups, it inevitably induces a reduction of the degrees of freedom, which makes the statistics useless. After conducting a post hoc analysis to compute the power of the test, it appeared that a one-tailed test with an effect size $d = 0.5$, an error probability of $\alpha = .05$ and two groups with relatively 7 and 11 participants, represents a power of .26. This indicates that there is a 26% probability that the test will reject the null hypothesis when the null hypothesis is false and consequently not make a false negative decision, a Type II error. If a power of .80 had been determined in order to obtain reliable statistical test results, the study should have included 102 participants. We were unable to find statistically significant differences between athletes who had a history of multiple concussions, compared with athletes who suffered less than three concussions. Since the power of the present study was too small and the groups were unequally distributed, we were unable to perform dependable statistical analyses. This induces that all results of the present study should be interpreted with caution and further testing should therefore be performed on a larger sample.

Additionally, one of the athletes suffering from multiple concussions appeared to score exceptionally high on PSI subtests, which had a large influence on the results of this small group. It is statistically useless to give a valid statement of the outcomes of a test in such a small group, especially when one of these cases differs this much from the other cases. If we would exclude this inconsistent case and perform the same tests on these data, we would probably obtain larger effect sizes and significant results on more subtests. Moreover, this case, with such high scores on PSI and WMI subtests, suffering from three or more concussions might also initially have an elite brain that – although it is damaged at the present time – processes information in a more developed and less complicated way compared to others. It has previously been demonstrated that elite athletes show superior performance at the level of perception, anticipation and decision making. This superior performance could, to some degree, be dependent on innate inter-individual differences (Yarrow, Brown, & Krakauer, 2009). Since the present study has a cross-sectional design, we cannot confirm these speculations due to the lack of information of the subject's performance on information speed processing and working memory tests before occurrence of the concussions.

The fact that we depended on concussion history self-reports as opposed to relying on clear evidence of medical records to address consequences of concussion limits our interpretation of the results. Since the present study is retrospective, it could occur that athletes fail to remember the presence of symptoms and are often less accurate with respect to duration and frequency of symptoms. This implies that concussions that are experienced in the past can be underestimated, or the severity of symptoms can be diminished, meaning that concussions are not being recognized or underrated. This can lead to significant problems, since it has been demonstrated that concussions have a deteriorating effect on cognitive functioning and previous concussions can enhance the risk for future brain injuries. Prospective studies with athletes followed longitudinally would increase the validity of the amount of concussions and its effects on processing speed and working memory, which leads to more reliable diagnosis and a more accurate report of concussions that are endured. This would also provide a better view on the severity of the concussions and the amount of diagnosed concussions. Several studies have proved that athletes are likely to underreport concussions or minimize or hide symptoms in order to prevent being removed from the game or – after being put beside the line – fear of being prevented from returning to play (Delaney et al., 2001; McCrea et al., 2004). Moreover, McCrea and colleagues (2004) found that individuals often do not report a probable concussion because they think it is not sufficiently serious to demand medical attention. It can also occur that an individual is unaware that the symptoms are caused by a concussion, since it has been proved that there is little knowledge on which symptoms follow concussions (Delaney et al., 2001, 2005; McCrea et al. 2004). It might therefore be constructive to provide psychoeducation or medical education in order to help individuals to listen to their body and brain. Delaney and colleagues (2001) found that both elite and non-elite athletes have a equally poor understanding of concussions. Additionally, McCrea et al. (2004) demonstrated that more than one third of athletes who did not report their injury did not recognize that they had suffered from a concussion based on the symptoms. Headache was found to be the most common symptom in both groups with recognized and unrecognized concussions (Delaney et al., 2001, 2005). In recognized concussions, confusion or disorientation appeared to be the second most common symptom, whereas dizziness was the second most common symptom in the unrecognized category (Delaney et al., 2005). Since these symptoms do not occur solely when suffering from a concussion, the symptoms can easily be unrecognized and thus not linked to a probable concussion. This emphasizes the necessity of campaigns or education to increase awareness of symptoms and consequences of concussions, since individuals should be able to recognize an experienced concussion and should be aware of the subsequent risks. Iverson and colleagues (2000) demonstrated that performance on tests of memory and executive functioning were equally performed by individuals with or without loss of consciousness. It has been proven that when athletes were provided with a definition of concussion and a description of injury signs and symptoms, they more readily recognized and confirmed to have sustained a concussion (McCrea et al., 2004).

4.5 Recommendations

Since the present study demonstrated that concussions appear to have a larger effect on information processing speed than on working memory, future research could be carried out in order to investigate whether information processing speed is more sensitive for concussions than working memory. It might therefore be important to include other neurological tests as well, since the present study has shown that there appeared to be an effect of concussions on several working memory areas.

Other aims of future studies are to examine whether playing positions have an influence on the amount and severity of concussions that ice hockey players suffer from, since previous research has stated that playing positions would diverge in the amount of concussions that are being experienced (Kuzuhara, Shimamoto, & Mase, 2009). Consequently, it should be investigated whether playing positions have an effect on the severity of the cognitive deficits that are being endured. Furthermore, it might be conducive to include more tests to investigate information speed processing and working memory with the aim of ascertaining the level on which one functions in order to get a more comprehensive analysis on one's abilities and possible deficits. This will additionally increase the reliability of the results, since the inclusion of more neuropsychological tests reduces the possibility on inaccuracies and consequently misinterpretations that can be caused by a single test. These dispositions will enhance the reliability of the obtained results and thus increase the effectiveness of the research. By means of applying these improvements, better understanding on the effects of concussions will be achieved. This will lead to the development in the field of comprehending concussions and providing advanced education to individuals considered to be at high risk for experiencing concussions. Future research should be carried out on a larger sample, since this would provide us with a larger amount of athletes sustaining multiple concussions. When including more participants, there will probably be less divergence in the outcomes, which could enhance reliability and generalisability to people suffering from severe concussions. This will give us the opportunity to obtain a better insight in the effects that concussions have on cognitive functioning, not only for elite athletes, but for the whole population. We recommend that future research should continue being carried out on ice hockey players, because of the recognized high amount of severe concussions (Cantu, 1998; Delaney, 2004; Delaney & Frankovich, 2005; Delaney, et al., 2005; McCrea, et al., 2010). To examine whether the effect of concussions is generalizable to a larger population, however, it is important to investigate other sports and activities with high incidence and high risk of concussions as well.

The method of assessing the amount of concussions that one has suffered from should be improved in order to ensure that concussions are not under- or overreported and to prevent the presence of unrecognized concussions. Therefore, prospective studies using computer-based neurocognitive assessment ImPACT (Immediate Postconcussion Assessment and Cognitive Test) to assess the occurrence and severity of concussions would be recommended. Thomas et al. (2011) demonstrated that there is a correlation between completing follow-up of ImPACT and reporting a delay in return to full activity that was not related to variations in symptom severity. Individuals completing follow-up were likely to report a steady return to normal activity and waited to return to full activity until symptoms had resolved. These findings suggest that ImPACT increases the awareness of individuals on the risks of early return to activity and may therefore reinforce a delayed return to activity. It also appeared that ImPACT provides an objective evaluation of cognitive deficits and detects differences in concussion severity that were not identified by means of clinical concussion grading. The recognition of concussions is important, since previous research has indicated that not only individuals enduring the concussion, but also the medical staff are often unable to recognize concussions (Delaney et al., 2001, 2005; McCrea et al. 2004 ,Thomas et al., 2011). ImPACT could thus provide the opportunity to facilitate the recognition of concussions and the severity of the subsequent symptoms, so that the classification of concussions is not solely evaluated by means of clinical concussion grading. The use of ImPACT will provide a reliable approach to examine the effect of the amount as well as the intensity of concussions on information speed processing and working memory (Thomas et al., 2011). It is important to take the severity of a concussion into account, since Pardini et al. (2010) demonstrated that more severely concussed subjects recruit more cognitive resources and have more difficulty in successfully completing a memory task.

Despite the fact that our study suggests no significant effect of multiple concussions, we support the recommendations of McCrea et al (2010), advising that there should be implications for injury prevention for concussion and the subsequent risks, since it appears that many individuals often do not recognize concussions and are frequently unaware of the risks following concussions. Therefore, it is important to educate and notify the society about the risks and sequelae of concussions. This could be achieved by means of an education campaign to better educate the complete population on the significant risks of head injuries and to elucidate the need to demand medical attention and care after experiencing symptoms from a head injury. These recommendations are also in accordance with the results of previous studies by Delaney et al. (2005).

5 Conclusion

We showed that concussions in ice hockey players cause a significant decrease in information processing speed. The results also indicated that concussions have no significant effect on working memory. Furthermore, our results implied that there is no cumulative effect caused by multiple concussions. We have therefore suggested implications for improved future research in order to further develop the current knowledge on the effects of concussions.

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Appendix 1) Informed consent form

Date:

____

Name:

____

By this I declare that I approve that the results of the testing procedure will be used for scientific publications. My name will not be used in any publication.

Signature:

____

Appendix 2) Scatterplots of performances on WAIS-III subtests

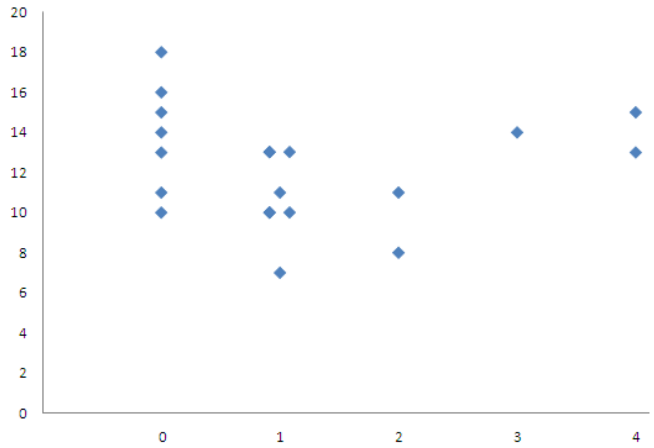

Figure 1. Symbol Search subtest. X-axis represents the amount of concussions suffered from; Y-axis represents the standardized score on the subtest.

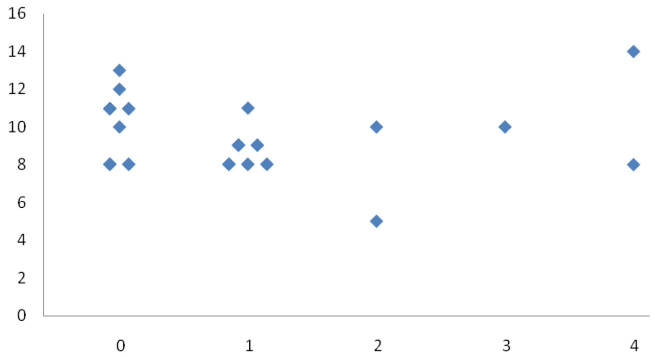

Figure 2. Digit Symbol subtest. X-axis represents the amount of concussions suffered from; Y-axis represents the standardized score on the subtest.

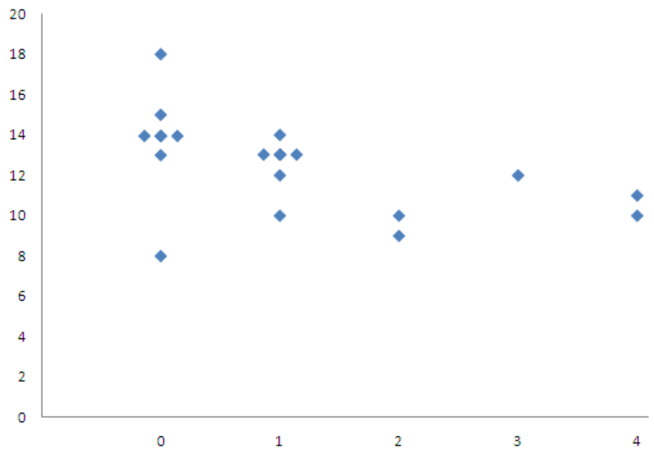

Figure 3. Digit-Letter Recall subtest. X-axis represents the amount of concussions suffered from; Y-axis represents the standardized score on the subtest.

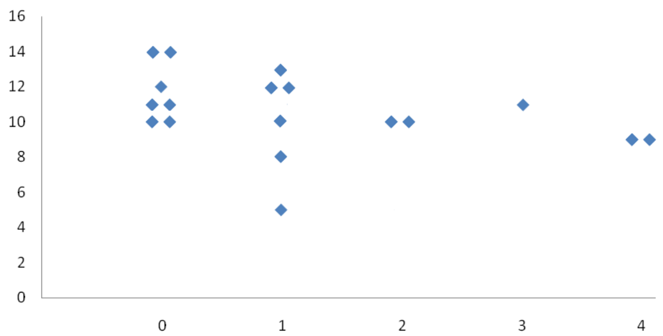

Figure 4. Arithmetic subtest. X-axis represents the amount of concussions suffered from; Y-axis represents the standardized score on the subtest.

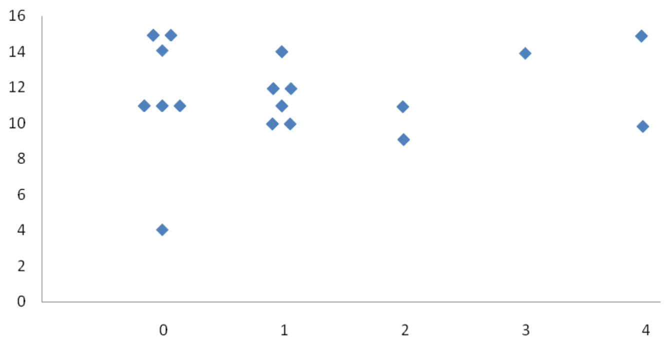

Figure 5. Digit Span subtest. X-axis represents the amount of concussions suffered from; Y-axis represents the standardized score on the subtest.