Development of a measure of visuomotor control for assessing the long-term effects of concussion

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Arts
in
Psychology

Waterloo, Ontario, Canada, 2009

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Recently, researchers have found evidence that after a concussion, residual visuomotor control deficits may linger longer than working memory or psychomotor speed deficits. All of the major computer administered test batteries currently in use for concussion management rely on examination of the latter tasks, and lack any measure of visuomotor control. The present research set out to develop a task to measure visuomotor performance. Using a touch-screen computer, the task required participants to point towards or away from (i.e., antipointing) a target in a design simmilar to an anti-saccade task. The task required participants to use visual information to execute controlled movements, and is designed to measure movement planning, execution performance and accuracy. The task was delivered to a large sample of healthy individuals to develop a normative performance data set. A self-report questionnaire was used to identify a small group of individuals from the normative population who were identified with a prior history of concussion. These individuals were directly contrasted with the healthy individuals. While only a few reported moderate or severe concussions, and information about recency and number of occurrences was unavailable, performance differences were observed –providing evidence of residual deficits. In particular, while concussed individuals were not slower, or less accurate overall than the healthy population on the task, they demonstrated unusual hand and spatial asymmetries. Future research will compare recently concussed individuals with the normative set developed here, and will make direct comparisons with existing computer administered test batteries to determine the efficacy of visuomotor tasks for detecting the long-term effects of concussion.

Acknowledgements

Dedication

This is dedicated my wife, Annette, and our son, Alexander.

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Chapter 1

Introduction

1.1 Concussive Head Injury

Scientific interest in sports concussion, a type of mild Traumatic Brain Injury (mTBI; Powell & Barber-Foss, 1999), has grown in recent years as evidence for the long-term effects of concussion have been mounting. Concussion involves a trauma to the brain tissue when an individual's head is subjected to a sudden physical jolt or impact. The resulting, often acute and debilitating symptoms, such as loss of consciousness or amnesia, usually subside within 2-14 days (Iverson, 2005; Johnston, McCrory, Mohtadi, & Meeuwisse, 2001). Epidemiological data indicates that concussion is the most common form of head injury experienced by athletes (Delaney, Lacroix, Leclerc, & Johnston, 2002), frequent not only in contact sports such as football or ice hockey, but also in sports which are often thought to be non-contact (e.g., basketball), and occurring at all levels of play from children to professionals (Powell & Barber-Foss, 1999).

Many aspects of concussion recovery are controversial and not well understood. While most of the data on concussion recovery address hospitalized populations, athletes experience different mechanisms and frequencies of injury, and face the pressing decision of when to return to sport, where they have a higher likelihood of experiencing further concussions (Echemendia & Cantu, 2003). Returning to play

while neurologically fragile, and potentially uncoordinated, increases the risk of further injury and the rare and potentially life threatening Second Impact Syndrome (SIS). Second Impact Syndrome is controversial, but thought to occur when an athlete sustains a second concussion while recovering from a previous concussion. It is postulated that this second impact results in more severe complications (Saunders & Harbaugh, 1984; Cantu & Voy, 1995; McCrory, 2001; McCrory & Berkovic, 1998). Even when not considering the risk for SIS, recent research indicates that the long term effects of repeated concussions may be more debilitating than once thought (Beaumont et al., 2009).

1.1.1 Long-Term Effects

While the long-term effects of sports concussion were once dismissed by coaches and athletes entirely, recent discoveries have reached the mainstream media. For instance, the results of an autopsy of former NFL player Tom McHale, aged 45, found that he had been suffering from chronic traumatic encephalopathy (CTE), a disorder that resembles Alzheimer's, but can only be diagnosed *post mortem* (Digravio, 2009). Chronic Traumatic Encephalopathy was originally described in boxers in 1928 as being 'punch drunk,' and presents with impulse control problems, erratic behaviour, emotional instability, depression, memory impairment, and an inevitable progression to dementia (McCrory, 2002; Corsellis, Bruton, & Freeman-Browne, 1973). The news made headlines in part because of the disturbing photographs of heavily damaged brain tissue, but more importantly because autopsies of six other former NFL veterans also resulted in diagnoses of CTE (Talan, 2008).

To better understand the long-term effects of sports concussion Beaumont and colleagues (Beaumont et al., 2009) compared older adults who had experienced sports concussions at least 30 years in the past with former athletes without a history of concussion. Relative to the controls, the former athletes with a his-

tory of concussion not only showed poorer performance on neuropsychological tests sensitive to age-related changes in cognition, but also showed abnormal neural responses when shifting attentional resources to novel stimuli. More specifically, electroencephalography (EEG) was used to monitor brain activity while the athlete was asked to identify occasional different-pitched tones among a series of regularly pitched tones (i.e., an 'oddball task'). While behavioural performance (i.e., reaction times and error rates) was equivalent to healthy controls, the injured athletes showed delays and attenuation of various components of the EEG wave form including P3a/P3b. Both reduced amplitude and increased latency of P3b have been associated with deficits in allocating attentional resources (Polich, Howard, & Starr, 1983; Kopp, Tabeling, Moschner, & Wessel, 2006). In addition results from trans-cranial magnetic stimulation (TMS) of the primary motor cortex indicate possible changes in motor inhibitory mechanisms, as well as decreases in motor speed (wrist rotation) post-concussion (Beaumont et al., 2009). Overall, the Beaumont and colleagues' study provides diverse evidence for chronic changes in cognitive and motor behaviour, evident decades after concussion. However, little is known about the medium to long-term effects of concussion (i.e., the Beaumont group essentially looked at the combined effect of concussion and aging). While the severity of the changes were not related to the number of concussions in this sample, all of the former NFL players diagnosed with CTE had experienced many concussions throughout their careers. For athletes returning to play after presumed recovery from a concussion, there is always the risk of further injury, making it vital to understand the effects that multiple concussions can have on the brain.

1.1.2 Cumulative Effects

As early as 1975, Gronwall and Wrightson found that adults with a history of concussion were less resilient to the effects of further concussions (Gronwall &

Wrightson, 1975). Using the paced auditory serial addition task (PASAT; a measure of information processing speed), the authors measured recovery of young athletes with and without any prior history of concussion after both groups had suffered either minor, or moderately severe concussions. Regardless of the type of concussion or history, all athletes demonstrated slower processing speed in the days following a concussion. However, regardless of the severity of the concussion, the multi-concussion patients took longer to recover than did athletes who had suffered their first concussion.

In a large, prospective study, 2905 college football players were baseline tested on a variety of measures (Guskiewicz et al., 2003). Of those players, 196 suffered a concussion during the study, 12 of whom suffered multiple concussions. Simply having a history of concussion lead to a three-fold increase in the probability of a player experiencing a sports concussion, and again, those with a history of concussion took longer to recover (30% increase in duration of symptoms). Importantly, of the 12 reported cases of repeat within-season concussions, 11 (91.7%) occurred within 10 days of the first injury (Guskiewicz et al., 2003).

A study of high-school American football players identified a large group of non-lethal, but SIS-like catastrophic head injuries with significant intra-cranial bleeding or edema (i.e., swelling; Boden, Tacchetti, Cantu, Knowles, & Mueller, 2007). The majority of athletes who suffered a catastrophic event had a prior history of concussion, many of whom had suffered a previous concussion within the same season. Perhaps most shockingly, a subgroup of these athletes were playing with known residual neurological symptoms from the prior head injury. It is apparent from these data that multiple concussions, particularly when sustained in a short time period, are a common precursor to catastrophic head injuries in athletes.

There is substantial evidence indicating that returning to play while recovering from a concussion is dangerous (Echemendia & Cantu, 2003; Guskiewicz, Riemann,

Perrin, & Nashner, 1997; Hugenholtz & Richard, 1982; Putukian & Echemendia, 1996). The existing evidence for reduced cognitive and motor performance, cumulative or lasting effects, and potential neural fragility post-concussion emphasize the need for accurate, reliable measurement of concussion recovery. An important goal of concussion management research should be to ensure that coaches and team doctors have reliable assessment tools that can convincingly demonstrate impairments in athletes, and to provide clear return-to-play guidelines based on well established empirical data to ensure that athletes never enter a playing arena in a compromised state.

1.2 Concussion Assessment and Management

There are several rating scales and accompanying guidelines to inform the decision of when to return to play after head injury (for review; see Johnston and colleagues (Johnston et al., 2001)). These systems are generally not empirically based, and rely heavily on athlete self-report (Echemendia & Cantu, 2003; Guskiewicz et al., 1997; Echemendia, Putukian, Mackin, Julian, & Shoss, 2001). As an alternative to these symptom based scales, several paper-and-pencil or computerized test batteries are commonly used as a measure of impaired cognitive performance post injury (Bazarian et al., 1999). First introduced to sports concussion by Barth (Barth et al., 1989), these neuropsychological tests have been shown to be sufficiently sensitive to identify memory (Killam, Cautin, & Santucci, 2005), attention (Binder, Rohling, & Larrabee, 1997), and psycho-motor speed (Collie, Makdissi, Maruff, Bennell, & McCrory, 2006) deficits in the weeks post concussion. Unfortunately, none of the batteries in use today measure fine motor control, the precise skill that an athlete needs to function at peak capacity and avoid further injury.

In a recent study of the effects of mild TBI in a hospitalized population, Heitger

and colleagues (Heitger et al., 2006) found that while standard neuropsychological tests showed normal performance one year after injury, some aspects of both upper limb and oculomotor performance were degraded on a target pursuit task. An oculomotor task was used which involved tracking eye movements when patients were asked to saccade away, and towards objects, execute sequences of saccades, and to follow smoothly moving objects on a computer screen (sinusoidal and random motion). An upper-limb visual motor task involved a 1-D tracking test using a 'steering-wheel' type input. The Rivermead Post-concussion Symptoms Questionnaire (RPSQ) was used as a subjective measure of residual symptoms. Even at 12 months, only 38.7% of patients reported to be entirely symptom free.

Of all the neuropsychological tests, only a test of verbal memory revealed cognitive deficits at 3 months, and at 6 months only on one sub-scale. Patients showed normal performance on all sub-scales of all measures at one year. At 12 months, oculomotor pursuit performance (average peak velocity on $60°s^{-1}$ sinusoidal pursuit) remained marginally slowed in the patients. Additionally, the brain injured patients showed robust impairments in upper-limb visual motor function at 6 months, residual latencies when manually object tracking, and marginally increased absolute pointing error at 12 months.

These results imply that while the symptoms of the brain injuries were still impacting the patients a year after the injury, the neuropsychological tests revealed no cognitive impairment. This, in itself is not necessarily indicative of a problem, as it could be indicating that neurological performance simply recovers before the symptomatic discomfort recovers. However, the fact that oculomotor and visuomotor performance was still impaired indicates that this is not the case.

1.2.1 Computer Administered Testing

In sports concussion, the older pencil-and-paper neuropsychological test batteries are gradually being supplanted by computer administered test batteries designed specifically for concussion management and return-to-play decisions in athletics. One such computer administered test of neurological performance is CogSport (for a full description, see Westerman, Darby, Maruff, & Collie, 2001). Tests are administered at the beginning of each season to obtain baseline performance, and are then administered multiple times post-concussion to monitor recovery. For this reason, CogSport is designed to minimize the problems other neuropsychological tests have when used repetitively. Specifically, CogSport has demonstrated excellent test-retest reliability even when multiple administrations are employed within a 24 hour period (Collie et al., 2003). That is, the tests employed in CogSport are not only relatively stable over long periods of time, but they do not appreciably suffer from practice effects over the short-term. Furthermore, an athlete attempting to fake poor performance at baseline is easily detected by virtue of excessive variance in reaction times when compared to a large normative sample, a feature not available in most pencil-and-paper tests. The battery requires 15 to 20 minutes to complete, uses playing cards displayed on the computer screen as stimuli, and contains several distinct tasks measuring simple and choice reaction time, decision making, problem solving, and short term memory.

As mentioned above, one important metric missing from existing test batteries in use today, including CogSport, is some measure of controlled movement (Collie et al., 2006). While several tests do involve a rapid motor components (e.g., digit symbol substitution, simple RT tasks used in CogSport and ImPACT (Collie et al., 2003; Iverson, Lovell, & Collins, 2005)), these tasks are more accurately described as measuring psycho-motor speed as opposed to precise visual motor control. For

example, the speed tests in CogSport require a key press on a standard keyboard which, although sensitive to changes in processing speed, is hardly a complex fine motor movement requiring visual guidance and on-line control. Very little attention has been paid to such fine motor control post concussion (Cremona-Meteyard & Geffen, 1994; Killam et al., 2005), which is striking given that this is precisely what is required to avoid further injury. Furthermore, beyond the ecological importance of such a metric, the addition of a fine motor, or visuomotor control measure may improve the sensitivity of existing neuropsychological test batteries (Guskiewicz, 2001; Guskiewicz, Ross, & Marshall, 2001; Heitger et al., 2006).

1.3   Speed Accuracy Trade-off

To determine the effectiveness of using visuomotor control performance as an indicator of post-concussive deficits, we developed an object-pointing task to directly contrast with CogSport (Locklin, Bunn, Roy, & Danckert, in press.). The task began with participants resting a finger on a fixation point on a touch screen computer. After a delay in each trial, a target of one of four sizes (4, 8, 15, and 29mm) would appear centrally and participants were instructed to lift their finger and point to the target as quickly and accurately as possible. We expected performance to conform to Fitts' law; as the target size decreases (i.e., as the precision requirements increase), both reaction time (RT) and movement time (MT) should increase. Unlike the simple reaction time task in CogSport, visually guided pointing of this kind requires a complex visual motor action involving controlled movement of the hand in space. Reaction time, in this case, involves the planning and initiation of that action. The task was administered to a group of athletes with and without a prior history of concussion, as well as a group of non-athletes with no history of concussion (Locklin et al., in press.). Post concussion symptoms were documented using a section of the McGill ACE (a condensed paper-and-pencil questionnaire;

unpublished), and a check-list of symptoms included in CogSport.

Those athletes with and without a history of concussion did not significantly differ in psycho-motor speed as measured by CogSport. Analysis of RT on the motor task revealed the predicted speed-accuracy trade-off based on Fitts' Law (main effect of target size) for both groups. Importantly, athletes with concussion were generally slower to respond to the appearance of a target than both control participants and athletes without a history of concussion.

Overall response time for each athlete with a history of concussion was then compared to the distribution of response time in the healthy population (Figure 1.1). Unlike the simple reaction time metric in CogSport, five of the concussed athletes fell well outside the range of performance for the non-concussed athletes, indicating that for these five individuals, RTs were strikingly slower than normal.

Unfortunately, none of the measures concerning symptomatology or concussion severity for the concussed athletes were informative in determining what differentiates those individuals who performed within the normal range from those who fell well outside the normal range.
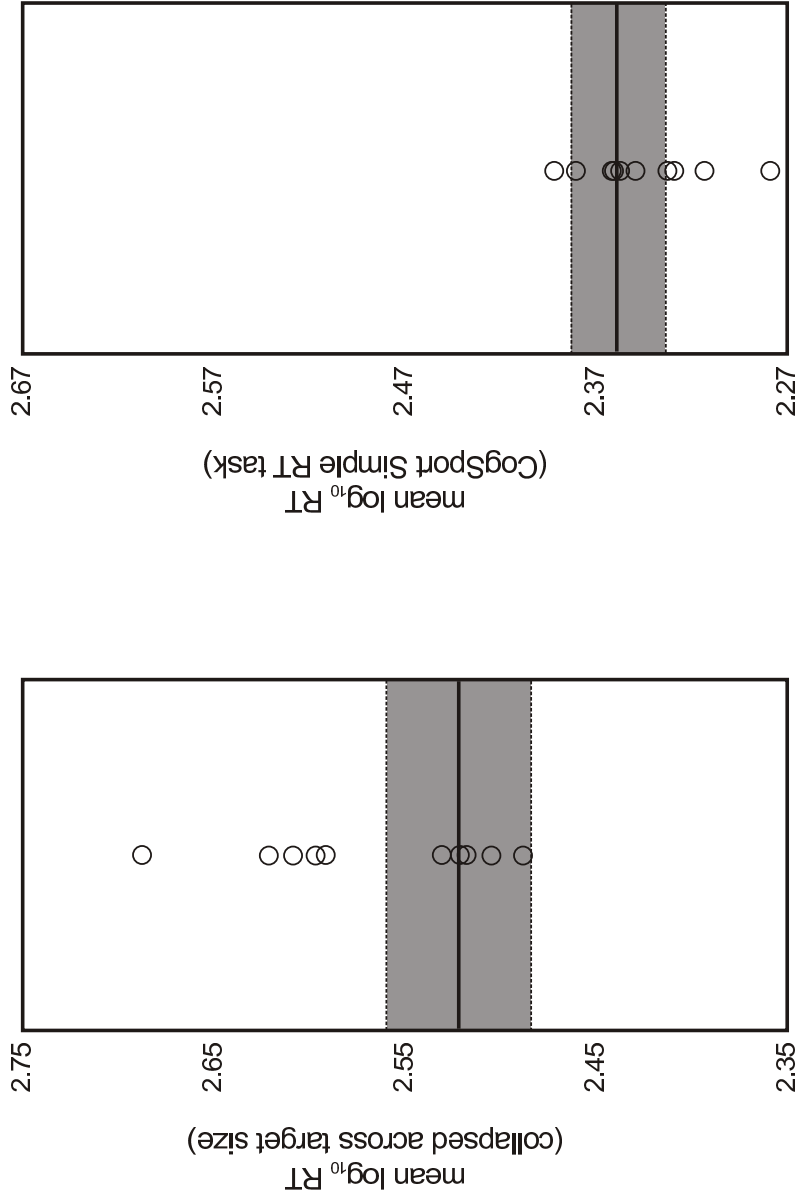
Figure 1.1: Mean log(RT) data from the motor task (left panel) and the simple RT task for CogSport (right panel) for the ten athletes with previous concussion (open circles) plotted against the mean log(RT) (dark horizontal line) and standard deviations (grey area) of the healthy athletes.

1.4 Current Research

While the results of our original study are promising, this falls short of providing a definitive argument for or against using visuomotor control as an index of post-concussive recovery. The pointing task was relatively simple, requiring very little spatial processing (i.e., the movement to be made on each trial was always in the same direction), and so may not have been sensitive enough to detect the subtle visuomotor deficits expected in non-symptomatic concussion victims. The goal of the current research was to develop a more challenging and sensitive measure of the effects of concussion on visuomotor control.

More specifically, a pointing task was developed using a variant of the anti-saccade task (Currie, Ramsden, McArthur, & Maruff, 1991; Hallett, 1978). In the most basic form of the anti-saccade task, participants are presented with targets and must either saccade to the target (the prepotent response) or inhibit that response and instead direct their eye movements towards the mirror-symmetric location. Here we replicated this task, substituting pointing movements for saccades; based on the colour of an appearing target, participants were to either point to the target or point to the mirror-symmetric location opposite the target. Performance from a large sample of healthy individuals was collected to determine normative performance characteristics for the measure. Subsequently, a group of individuals who had a history of concussion were identified by self-report, and their performance was contrasted with that of the healthy population.

Chapter 2

Method

2.1 Participants

The experiment included 123 individuals from the undergraduate population at the University of Waterloo (50 female, mean age= 19.7, $SD = 1.8$). Sixteen participants reported being left handed and were not included in the analysis.

A prior history of concussion questionnaire (Appendix A) was used to divide the participants into two groups, those with (Table 2.1) and without a history of concussion ($N = 104$). Participants were defined as "Concussed" if they reported a past concussion which included a loss of consciousness, and if they experienced at least one of the following symptoms: vomiting, unsteadiness, nausea, memory loss, headache, fatigue or blurred vision. All participants who reported a history of concussion met the above criteria. Participants with a history of major brain injury or surgery were removed from the data-set ($N = 2$). Only two of the concussed participants were female, so the analysis was restricted to the male participants. Given these restrictions, the reported analysis was conducted with 44 healthy right-handed male participants, and 13 right-handed male participants with a history of concussion.

All participants gave informed, written consent and the experimental protocol was cleared by the University of Waterloo ethics committee.

Subject	Sex	No. Concussions	Cause of latest concussion	Loss of consc. (Mins)	Headache	Nausea	Unsteadiness	Fatigue	Blurred vision	Memory loss
1	F	2	Cycling	1	N	N	N	N	N	Y
2	M	1	Ran into furnace	10	N	N	Y	N	Y	N
3	M	1	Hit by golf ball	1	N	N	Y	N	N	N
4	M	1	Hockey	>1	Y	N	Y	N	N	N
5	M	1	Hockey	2	Y	Y	Y	N	Y	Y
6	M	1	Boxing	>1	Y	N	Y	N	N	N
7	M	5	No data	5	Y	N	N	N	Y	Y
8	M	1	Car accident	>1	Y	N	Y	Y	Y	N
9	M	1	Trampoline	>1	Y	Y	Y	Y	Y	N
10	M	1	Cycling	120	N	N	N	Y	N	Y
11	M	1	Karate	No data	Y	Y	N	Y	Y	Y
12	M	1	Tobagganing	240	Y	N	N	Y	N	N
13	M	1	Collision with person	>1	Y	N	N	N	Y	N
14	M	2	Skiing	>1	Y	N	N	N	N	N

Table 2.1: History of the Concussed Participants

2.2 Apparatus & Procedure

Participants completed a written prior history of concussion questionnaire (Appendix A), followed by the computer administered visuomotor test described below.

The motor task utilized a Pentium IV class PC with a 1 Gb of RAM, and a 17 inch ViewSonic E70fb CRT touch screen monitor. The monitor had a refresh rate of 85hz, operated at a resolution of 480x600 during the task, and recorded touch with a precision of 0.54mm. The monitor provided both stimulus presentation and response input. Participants were instructed to position their fixed-leg chair at a comfortable arms-length distance from the screen to avoid fatigue during the task, and they were free to move their head and eyes. The touch-screen was individually calibrated for each participant using the tool provided with the ViewSonic touchscreen.

One of the unfortunate challenges to participants with a pointing task is the upper limb fatigue from holding one's hand in front of the body for an extended period of time. To alleviate this problem, the task was designed to allow participants to take breaks at any time. Participants were notified that refraining from placing their finger on the starting point would prevent the next trial from beginning, and thus would allow a break at their convenience.

The task is intended to measure fine motor control in a context where movement plans may need to be inhibited or recalculated. Two blocks were performed (one for each hand) totalling 108 trials. For each trial, participants were presented with a black screen containing a 15x15 mm starting point at the bottom centre. They were instructed to hold their finger on the starting point until a target appeared. After a delay period jittered between 500ms and 1500ms, a 15 x 15 mm square target would appear in the centre of one of the four quadrants of the screen. Target appearance in the upper or lower quadrants of the screen has important implications

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for the biomechanics of the motion. Unlike similar tasks, because participants were free viewing, they do not represent upper and lower visual fields. Instead, because of the starting point at the bottom of the screen, they represent long and short ballistic movements, with different affordances for on-line correction abilities. If the participant lifted his or her finger off the starting point before the target appeared, a prompt appeared reminding the participant to replace his or her finger on the starting point, and the trial would re-start.

The target was one of two equaprobable colours (red or white) and participants were instructed to lift their finger and point to white targets as quickly and accurately as possible. When red targets appeared, participants were instructed to "anti-point" to the opposite side of the screen. To avoid introducing between-subject variance with differing tasks, everyone received the same colour-task mapping.

The time interval from the appearance of the target on the screen to the moment the participant's finger lifted off the screen was considered the reaction time (RT). The time interval from finger-lift to the moment the participant touched the screen, divided by the distance from start- to end-points, was considered the movement speed (MS). The touch and target locations in both X and Y dimensions were recorded and used to calculate the error magnitude and direction. Trials were marked incorrect if the participant pointed to the incorrect side of the screen for the trial type.

2.3 Analysis

To remove anticipatory responses from analysis, individual trials were removed when response times were less than 100ms or movement durations were less than 50ms. Trials where the movement was not completed were also removed. Several

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participants began the task with the incorrect colour mappings, and the experimenter gave additional instructions after a few trials. To remove this effect, the first ten trials of each block were considered "practice" and removed from the analysis.

Three separate mixed-effects Analysis of Variance's (ANOVA's) were conducted. One for each of RT, MS and error outcome measures. The main experimental manipulation, pointing vs. anti-pointing was included as a within-subject factor for the RT and MS analysis. Because precision on anti-pointing trials makes little sense, the error analysis included only pointing trials. All three analyses included two factors to represent target location. The first factor, lateral target location (LTL) was included to measure differences in responding to targets appearing in either side of space. The second factor, vertical target location (VTL) represented differences between short and longer pointing movements. Finally, a factor representing the hand used for a particular block was included to measure hand asymmetries.

In addition to the within-subject experimental manipulations, a between-subject variable distinguished those who had experienced a history of concussion. Because the intended outcome of this line of research was to develop a test that will be administered to athletes, the normative performance parameters should only be valid for those without a history of concussion. Not only are many of the athletes to be tested going to have a history of concussion, the effectiveness of any such test may be most critical for those with a history of concussion. For this reason, each analysis was performed including this subgroup, and a between-subject factor was utilized to identify indications of performance differences in this subgroup.

Analysis of variance and protected t-tests involved log transformed RT values to normalize the highly skewed reaction time data. For illustrative purposes, untransformed RT values were used for calculating 95% confidence intervals (denoted '95% CI' where used). A significance value of $\alpha = 0.05$ was used for all statistical tests

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and a Welch modification to the degrees of freedom was used to correct for unequal variance when conducting t-tests between the two groups (denoted 'corrected t').

Chapter 3

Results

3.1 Reaction Time (RT)

The main task manipulation (pointing vs. anti-pointing), accounted for a significant portion of the RT variance ($F(1, 55) = 155$, $p < 0.0001$). Collapsing across other factors, RT means for pointing were significantly faster than anti-pointing ($t(56) = 13.6$, $p < 0.0001$). While participants responded to pointing targets within 420-455ms (95% CI, $M = 437$, $SE = 8.79$), anti-pointing responses were slowed relative to pointing by 39-53ms (95% CI, paired $t(56) = 13.1$, $p < 0.0001$). See Table 3.1 for a complete set of means.

The lateral location of targets also accounted for a significant portion of RT variance ($F(1, 55) = 8.04$, $p > 0.01$), indicating a lateral asymmetry in response readiness for planning actions. A protected t-test comparing the RT means for each hemispace indicated faster responses to right versus left targets ($t(56) = 2.43$, $p = 0.02$). This represents a small, but significant, 2-10ms difference in untransformed RT (95% CI, $t(56) = 2.86$, $p < 0.01$).

There was a significant interaction between VTL and the group variable ($F(1, 55) = 8.53$, $p < 0.01$). With respect to the the non-concussed individuals only, responses to upper targets were faster than to lower-onset targets ($t(43) = 3.08$, $p < 0.01$). When considering untransformed data, this difference amounts to 4-18ms (95% CI,

		RT	MS	xerror	yerror
Task	Point	6.06 (0.14)	0.487 (0.14)	3.89 (1.0)	8.89 (2.1)
	Anti-point	6.15 (0.14)	0.450 (0.17)		
	Mean Difference	0.10 (0.05)*	0.038 (0.07)*		
LTL	Left	6.11 (0.14)	0.469 (0.15)	4.36 (1.6)	8.94 (2.3)
	Right	6.10 (0.14)	0.467 (0.15)	3.41 (1.3)	8.85 (2.4)
	Mean Difference	0.01 (0.03)*	0.001 (0.03)	0.96 (1.7)*	0.09 (2.1)
VTL	Top	6.09 (0.14)	0.540 (0.16)	3.74 (1.0)	6.99 (2.7)
	Bottom	6.12 (0.14)	0.395 (0.15)	4.04 (1.1)	10.8 (3.6)
	Mean Difference	0.03 (0.05)*	0.145 (0.06)*	0.30 (0.8)*	3.85 (4.9)*
Hand-Used	Dominant	6.11 (0.14)	0.457 (0.15)	3.90 (1.2)	8.77 (2.3)
	Non-dominant	6.10 (0.15)	0.457 (0.15)	3.88 (1.1)	8.99 (2.3)
	Mean Difference	0.01 (0.08)	0.022 (0.08)*	0.02 (1.1)	0.22 (1.7)

Table 3.1: Means and (standard deviations) for each level of each factor (N=57). Columns contain values for each of the four outcome variables. A (*) indicates a significant difference using a protected t-test.

$t(43) = 3.23$, $p < 0.01$). For clarity of discussion, see the dedicated "Concussion History" section for an analysis of the concussed individuals. The remaining within-subject variable, hand used, did not account for a significant portion of response variance ($F(1, 55) = 2.67$, $p = 0.1$), and no other interactions were significant.

3.2 Movement Speed (MS)

The same analysis was performed with MS as with RT, with the exception that movement speed was not log transformed. Importantly, the main task manipulation accounted for a significant portion of movement variance (P/NP; $F(1, 55) = 17.2$, $p < 0.001$). While participants pointed to targets with an average speed of 0.45-0.52 mm/ms (95% CI, $M = 0.49$, $SE = 0.02$), anti-pointing was reliably 0.02-0.06mm/ms slower (95% CI, paired $t(56) = 4.22$, $p < 0.0001$).

The task manipulation (pointing vs. anti-pointing) showed a significant interaction with lateral target location (LTL; $F(1, 55) = 6.18$, $p = 0.02$). As can be observed in Figure 3.1, pointing movements to targets on the right were faster than pointing to targets on the left ($t(56) = 2.76$, $p < 0.01$). Conversely, anti-pointing away from targets on the left side (i.e., pointing to the right) was faster than anti-pointing from targets on the right side (i.e, pointing to the left; $t(56) = 2.43$, $p = 0.02$). This represents a general bias where any sort of pointing to the right side was 0.01-0.03mm/ms faster than pointing to the left (95% CI, $t(56) = 2.84$, $p < 0.01$). Note that this may be an effect specific to right-handed individuals.

The main effect for Vertical target onset location (VTL) was also significant ($F(1, 55) = 253$, $p < 0.0001$). While a participant's average pointing movement speed for the lower onset targets was 0.36-0.43mm/ms (95% CI, $M = 0.39$, $SE = 0.02$), movements for the upper onset targets were reliably 0.13-0.16mm/ms faster (95% CI, paired $t(56) = 18.6$, $p < 0.0001$).
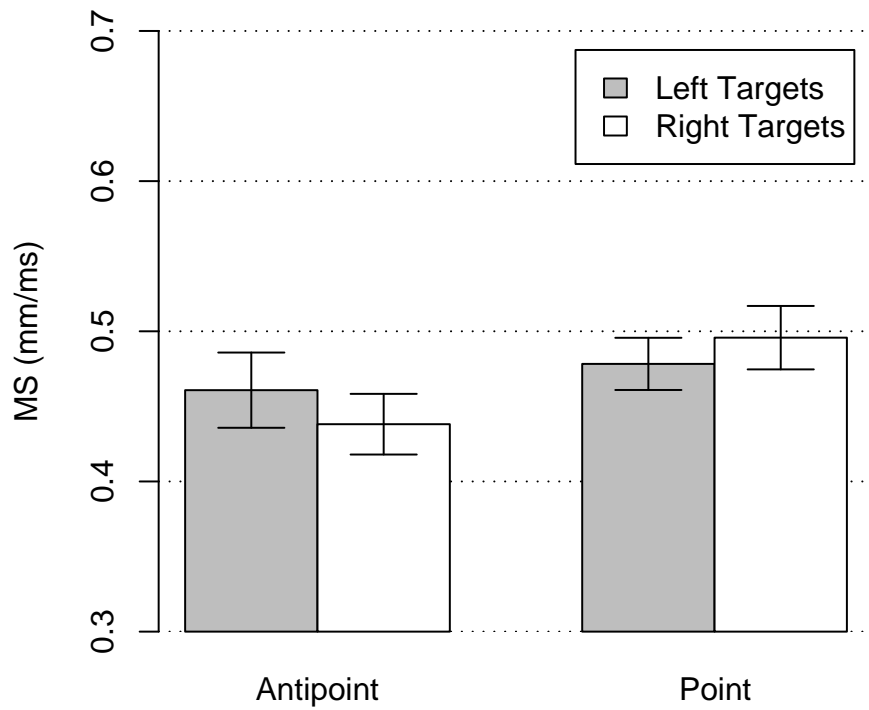
Figure 3.1: Movement speed participant means for pointing and anti-pointing trials. Dark bars represent targets appearing on the left side of the screen, and white bars represent targets on the right. The crossover represents a lateral bias where by gesturing to the right side is faster, whether pointing or anti-pointing. Error bars represent 1 standard error.

There was a significant interaction between hand used and group ($F(1, 55) = 7.81, p < 0.01$). With respect to the non-concussed individuals only, there was no indication of any hand asymmetry with regard to movement speed ($t(43) = 0.63$, $p = 0.5$). This interaction is further explained in the 'Concussion History' section.

3.3 Pointing Precision

The absolute value of the trial-by-trial error data gives an estimate of the typical participant's pointing precision. Participant error was collected as lateral and vertical error seperately. These two error measurements were included in the analysis as seperate factors so that dimension specific error effects could be analized.

There was a main effect of lateral target location (LTL; $F(1, 55) = 5.67$, $p = 0.02$). The main effect here, represents an effect while collapsing across, or at a mean value of the two error dimensions. For the sake of clarity, the radial error (i.e., the magnitude of the vector sum of the two error dimensions) was computed. As a result, while participants made, on average, 9-10mm of error when pointing to targets on the right side (95% CI; $M = 9.55$, $SE = 0.32$), they trended towards making up to an additional 1mm of error when pointing to the left (95% CI; paired $t(56) = 1.8$, $p = 0.08$).

A significant interaction was present between vertical target location (VTL) and the error dimension component ($F(1, 55) = 16.4$, $p < 0.001$). In this case, the effect of VTL can be thought to depend on the dimension of error being considered. As can be seen from Figure 3.2, While lateral error is slightly, but significantly, larger when pointing to lower-onset versus upper-onset targets (0.1-0.5mm; 95% CI; $t(56) = 2.9$, $p < 0.01$), vertical error shows an asymmetry in the same direction, but an order of magnitude larger (3-5mm difference, 95% CI; $t(56) = 5.9$, $p < 0.0001$). Notably, vertical error is always greater than lateral error ($t(56) = 9.41$, $p < 0.0001$

for upper, and $t(56) = 13.7$, $p < 0.0001$ for lower onset targets).

As with movement speed, there was a significant interaction between hand used and group ($F(1, 55) = 13.9$, $p < 0.0001$). Non-concussed participants show a typical precision bias where they point more precisely with their dominant hand than their non-dominant hand (0.1-0.7mm, 95% CI; $t(43) = 2.40$, $p = 0.02$). The concussed individuals are discussed below.

3.4 Concussion History

As expected, the subgroup of individuals with a history of concussion performed somewhat differently across the three measures. There was no group main effect (For RT, $F(1, 55) = 0.29$, $p = 0.5$, for MS, $F(1, 55) = 0.22$, $p = 0.6$, for error $F(1, 55) = 0.20$, $p = 0.7$). However, several interactions with concussion history indicate that this subgroup performs somewhat differently.

The between-subject factor of concussion history on RT was present in a significant interaction with VTL ($F(1, 55) = 8.53$, $p < 0.01$). While both concussed and non-concussed participants responded to upper-onset targets faster than lower-onset targets ($t(12) = 6.80$, $p < 0.0001$; and $t(43) = 3.08$, $p < 0.01$ respectively), a comparison of difference scores between the two groups indicate that concussed participants showed a larger asymmetry (corrected $t(29) = 3.34$, $p < 0.01$). The asymmetry can be observed in Figure 3.3. It may be that the interaction is driven by concussed participants responding faster to upper targets, however, this group difference was not significant ($t(31) = 1.21$, $p = 0.2$).

Concussed individuals also moved at somewhat different speed than non-concussed individuals, depending on the hand used (i.e., hand used by concussion history interaction; $F(1, 55) = 7.81$, $p < 0.01$). While healthy participants do not show a hand asymmetry with regard to movement speed ($t(43) = 0.63$, $p = 0.5$), concussed
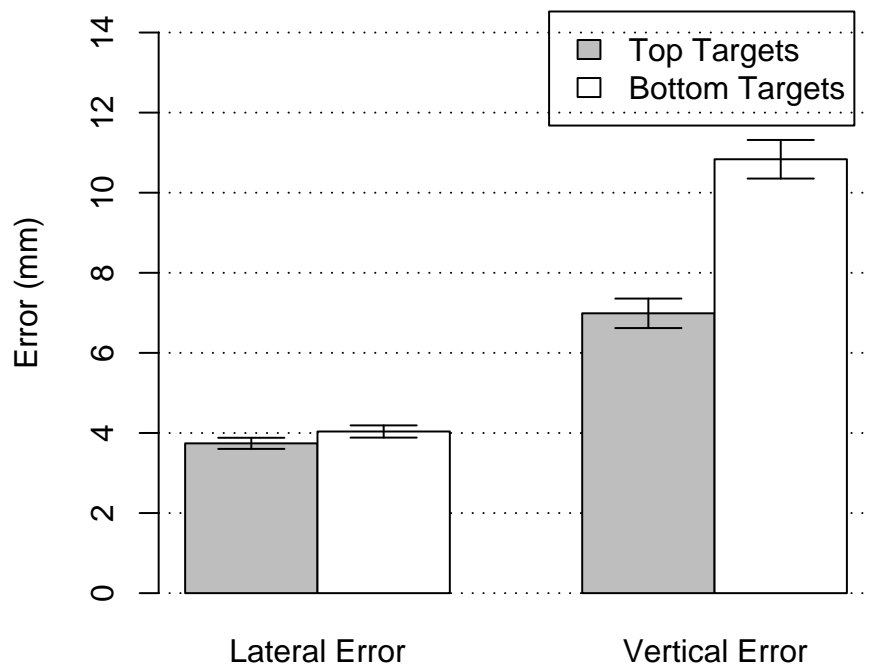
Figure 3.2: Lateral and vertical error sub-component participant means. Dark bars represent pointing to the top of the screen, and white bars represent pointing to the bottom of the screen. Error bars represent 1 standard error.
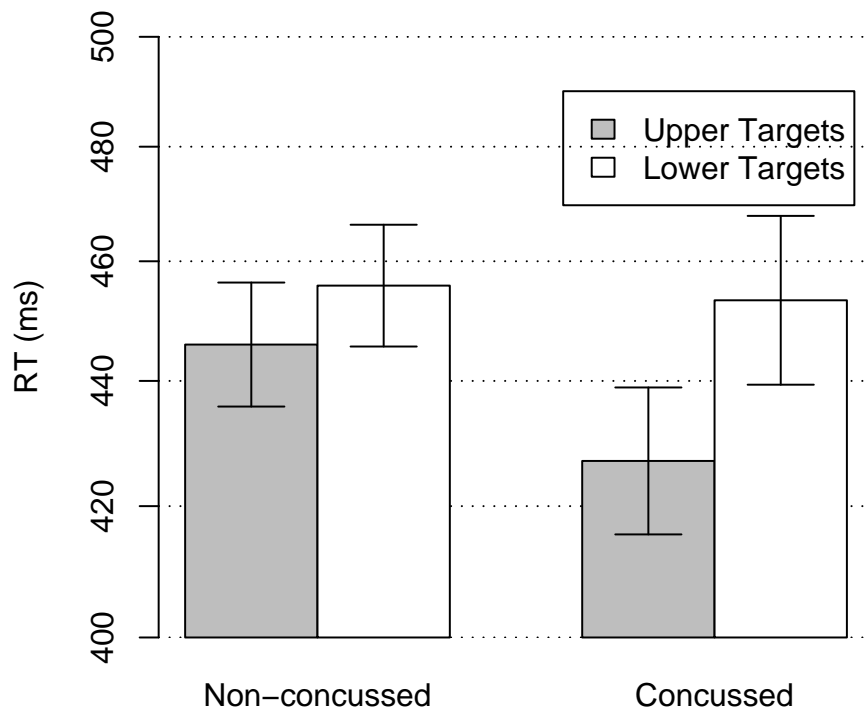
Figure 3.3: Comparison of group means. Dark bars represent trials where targets appear at the top of the screen, white bars the bottom of the screen. The concussed participants show a greater top-bottom asymmetry in response time. Despite the appearance that the asymmetry is driven by faster RT to upper-targets in the concussed individuals, this observation is unsupported by the data (corrected $t(31) = 1.21$, $p = 0.2$). Error bars represent 1 standard error.

participants show significant hand differences in movement speed ($t(12) = 3.32$, $p < 0.01$). Asymmetry scores, were larger for concussed than non-concussed individuals (i.e., difference scores between left and right hand; corrected $t(19) = 2.7$, $p = 0.02$). See Figure 3.4

As with movement speed, for error, there was a significant interaction between hand used and history of concussion ($F(1, 55) = 13.9$, $p < 0.0001$). While non-concussed participants show a typical precision bias where they point more precisely with their dominant hand concussed participants showed the opposite pattern, where pointing with their non-dominant hand was 0.3-1.3mm more accurate than with their dominant hand (Figure 3.5; 95% CI; $t(12) = 3.41$, $p < 0.01$).

3.5 Practice Effects

An important characteristic of a test is that it is internally consistent. Correlations between subject means for trials in the first and second half of the task were computed. For healthy participants, RT, MS, and precision were correlated between the first and second half of the test ($r(42) = 0.91$, $p < 0.0001$ for RT; $r(42) = 0.96$, $p < 0.0001$ for MS; and $r(42) = 0.67$, $p < 0.0001$ for error). The same results were found for the concussed participants ($r(11) = 0.85$, $p < 0.001$ for RT; $r(11) = 0.97$, $p < 0.0001$ for MS; and $r(11) = 0.85$, $p < 0.001$).
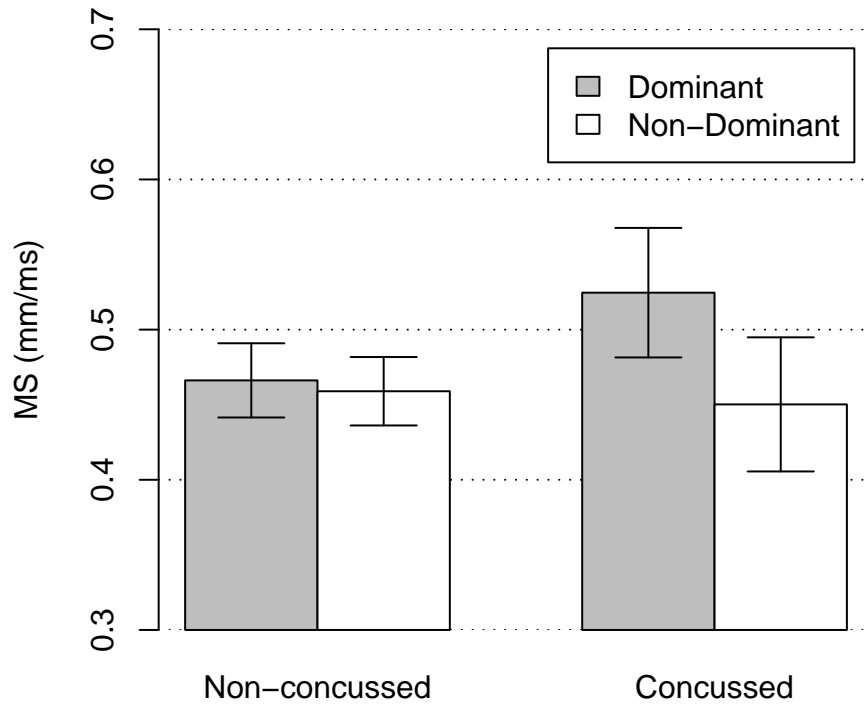
Figure 3.4: Movement speed participant means for the two groups. Dark bars represent pointing with their dominant hand, and white bars, using their non-dominant hand. Note that because of the increased variance between subjects relative to within, it's not possible to tell whether concussed participants were actually faster with their dominant hand than non-concussed participants (as implied by the means, corrected $t(21) = 1.2$, $p = 0.3$), or whether they were slower with their non-dominant hand than their healthy counterparts (corrected $t(19) = 0.17$, $p = 0.9$). Error bars represent 1 standard error.
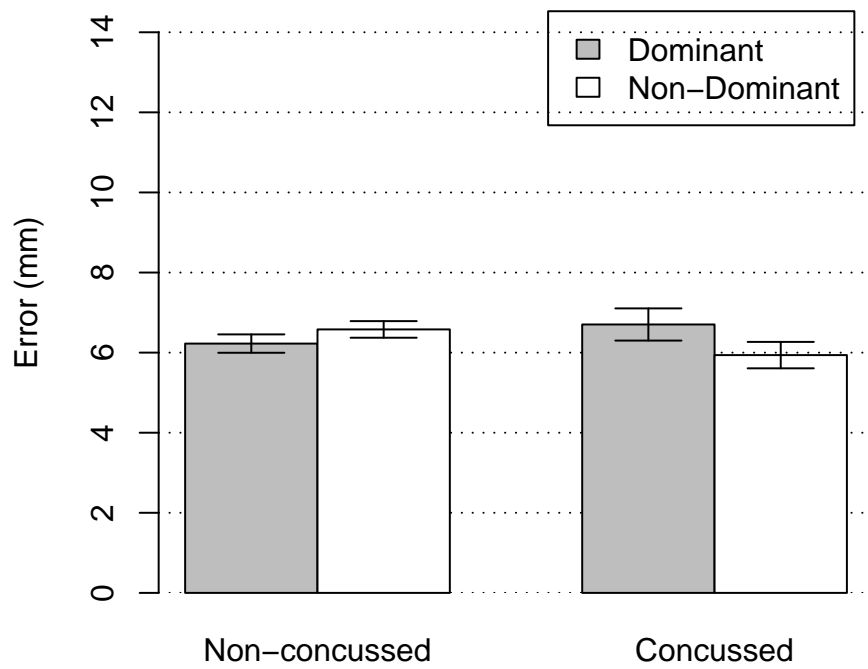
Figure 3.5: Pointing error for the two groups. Dark bars represent pointing error when using their dominant hand, and white bars, when using their non-dominant hand. The two groups show opposite, and significant asymmetries between the two hands. Error bars represent 1 standard error.

Chapter 4

Discussion

The primary goal of the current research was to develop a task which is sensitive to subtle visuomotor control differences. The rationale is that a task which can challenge the human visuomotor system and measure small changes in performance, may be capable, with some refinement, of measure subtle visuomotor changes that may occur post-concussion. A subgroup of the participants tested reported a prior-history of concussion. An important consideration when designing a task to measure an athlete's visuomotor performance post-concussion is the performance characteristics of this common sub-population.

4.1 Normative Performance

Importantly, every experimental manipulation provided robust, measurable changes in visuomotor performance in at least one of the three outcome variables. The main task manipulation, pointing vs. anti-pointing, affected both applicable outcome variables: movement planning and execution time. Even though the two types of trials were equiprobable, it is reasonable to expect that pointing or grasping towards an object is a more natural action than pointing away from it. It is s not surprising then, that performance mirrors other research where participants must inhibit a prepotent response (pointing) and execute another. In other words, participants

presumably begin planning, or even executing the pointing movement reflexively on target onset, then must cancel or change the action when the non-default anti-pointing cue is registered. As would be expected, then, anti-pointing comes at a cost, both in reaction and execution speed.

In order to challenge the visuomotor system, and reduce practice effects on performance, both the lateral and vertical target onset locations were varied. Vertical target onset location served to provide short and longer distance movements. Short movements are more spatially constrained and provide less opportunity for the visuomotor system to make corrections in-flight. As a result, participants took more time to plan movements to the lower targets, moved to them more slowly, and made larger errors. Thus, this aspect of the task should provide a sensitive metric against which the effects of concussion can be measured.

The lateral target onset manipulation allowed analysis of pointing behaviour in the participant's peripersonal left and right space. These right handed individuals responded reliably faster to targets appearing in the right space, and also moved faster while executing these responses in right space (whether pointing or anti-pointing). They were also more precise when pointing in right space. This may be a reflection of the selection of right-handed only participants for analysis. Left-handed individuals may show a different bias.

Surprisingly, participants show no differences in response or movement speed between their dominant and non-dominant hand. They do, however, point with more precision when using their dominant hand.

4.2   Concussed Participants

The participants with a history of concussion provide a meaningful contrast to all of the normative performance characteristics described above. Differences in this

population may be a result of changes post-concussion. Differences that this group presents provide an indication of important avenues to pursue in future research where pre- and post-concussion data collection can be made, and the effects of concussion can be empirically disambiguated from pre-existing differences.

Interestingly, the concussed participants showed unusual hand asymmetries relative to the healthy individuals. Unlike the equally speeded hands of their non-concussed counterparts, they moved considerably quicker with their dominant than non-dominant hand. While this may at first glance appear to be a performance advantage for the concussed individuals, they were also less precise with that hand, indicating that they may have been acting more hurried, and exhibiting a more strict speed-accuracy trade-off than the non-concussed participants. This may well be an important point for future concussion management. If, at baseline, non-concussed athletes perform much like our healthy individuals (i.e., no hand asymmetries), then any asymmetries in speed-accuracy trade-offs post concussion would be informative of changes in visuomotor control.

The other performance characteristic that was markedly different for the concussed participants was their vertical asymmetry in responses. While both groups responded more quickly to targets appearing in the upper part of the screen, this difference was larger for the concussed individuals. If the principle difference between upper and lower targets is a difference in kinematic constraints, the results of this manipulation suggests that concussed individuals are more sensitive to movement constraints than are healthy individuals. This type of result provides two valuable insights in developing a task that identifies visuomotor performance changes in concussion. First, the degree of spatial constraint in a movement may be an important consideration when developing a sensitive task. Second, differences in performance between differently constrained movements may be a good indicator, in and of themselves, of concussion-related changes. Regardless, it is important

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to recall that such performance characteristics would likely be impossible to detect with a simple button press response –a movement that is almost completely constrained.

4.3   Conclusion

Effectively, the task reported here appears to be sensitive to subtle visuomotor performance differences such as lateral asymmetries and differences between movements based on distance differences of only a few centimetres. The concussed participants in this study were not currently symptomatic, and were not exhibiting overt motor problems. The ability to measure any visuomotor differences in this group is a testament to the potential this type of task has as a measure of concussion recovery. These people, however, were not in a recovery phase or under treatment for a concussion. As a result, the differences found here are simply an indication of where to look when conducting the necessary future research to develop a task capable of measuring the recovery of visuomotor performance post concussion. Ultimately, such a task will need to provide normative results indicating the likelihood of re-injury. Future research will need to follow concussed athletes over weeks and months post-concussion, and preferably with pre-concussion baseline data. It will be important to determine a typical recovery curve for each applicable measure and the potential effects of historical personal events (e.g., previous concussions) on recovery. This research will require larger samples of participants and normative data from various groups to be useful in sports medicine (e.g., both genders, handedness, various ages and skill levels). There is a need, however, to easily and accurately measure concussion recovery so that serious injury can be prevented, keeping athletes from returning to play while still neurologically fragile, or simply un-coordinated. This research and the past research discussed here points to an avenue to accomplish this goal which shows promise, and while still in its infancy,

should be pursued to determine its usefulness.

APPENDICES

Appendix 1, Prior History of Concussion Survey

Prior History of Concussion Survey

Please answer the following questions carefully to the best of your knowledge.

1. Have you ever suffered from an injury to your brain or undergone any brain surgery? ☐ Yes ☐ No

     If yes, please describe the nature of that injury / surgery, include when it occurred, how long you were unconscious for and what, if any, consequences you have suffered.

2. Have you ever suffered from concussion (i.e., loss of consciousness)? ☐ Yes ☐ No

3. Do you regularly participate in contact sports?

     1. If yes, how many times a week (on average) do you spend participating in contact sports?

     2. How many years have you regularly participated in contact sports?

If your answer to question 2 was NO, you are done. If you answered yes, please continue.

4. How many concussions have you experienced?

How long ago where your concussion(s)?

What was the cause of your concussion(s)?

5. For each concussive episode, please indicate the amount of time you were unconscious (obviously your answer may rely on what others told you at the time try to be as accurate as possible according to what you were told or what doctors told you).

6. After each concussive episode what, if any were your symptoms?

    ☐ headache ☐ nausea ☐ unsteadiness ☐ fatigue

    ☐ vomiting ☐ blurred vision ☐ memory loss

For each of the symptoms above (and for each concussive episode separately), please indicate the amount of time you experienced the symptom.

7. If you have any other comments regarding your concussion(s) please indicate these in the space provided below.

Thank you for completing this survey.

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