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NON-LINEAR ANALYSIS OF VISUAL-MOTOR TRACKING PRE- AND POST- HEADING IN COLLEGIATE FEMALE SOCCER ATHLETES

By

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A plan B research project submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

In

Health and Human Movement

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Abstract

Context: There has been minimal examination of the long-term effects of sub-concussive events, particularly related to non-linear aspects of motor performance. Examining the structure of performance, using nonlinear techniques, following sub-concussive events may lend insight into subtle, but significant changes in motor behavior. **Objective:** This study examined the effect of performing a bout of headers on visual motor control in a group of female soccer athletes. We specifically examined the amount of error during visual-motor tracking (root mean squared error; RMSE), the regularity of the movement structure (sample entropy; SampEn), and the lag present between the target signal and the participant's output. **Design:** Participants were tested before practice, after practice, and 24-hour post practice. This process was done twice, with a heading drill completed at the end of practice during the second round of testing. **Setting:** Testing was completed in two private offices within the athletic training facility. Each participant used the same computer for each of her sessions. **Participants:** Nine, Division I, female soccer athletes completed the testing sessions. Every subject acted as their own control, completing the first round of testing without the influence of headers and the second round of testing following the soccer heading drill. **Results:** RMSE decreased over time for all conditions. Due to potential effects of learning, a projected value for RMSE was calculated for the post and 24-hour post soccer heading sessions. There was a significant increase in RMSE following headers when compared to the projected value. There was, however, no significant effect of headers on the regularity (SampEn) of the waveform produced. Additionally, there was significantly greater lag seen in the waveform with limited visual information compared to the waveform with full visual information. The lag did not change following performance of headers.

Introduction

A common consequence of sport participation is head injury, specifically concussion. To fully understand the significance that concussions have in athletics, there are several components to consider. These include understanding what a concussion is, what the consequences are, the prevalence of concussions in athletics, and how concussions are diagnosed. A concussion is defined as "a traumatic-induced alteration in mental status that may or may not involve loss of consciousness" (Broglio, et. al., 2014). The National Athletic Trainer's Association (NATA) states that concussions occur when a force (direct or indirect) is applied to the skull, resulting in a "rapid acceleration or deceleration of the brain" (Broglio, et. al., 2014).

While short term consequences of concussion can be seen in the immediate symptoms that present following a concussive blow, the long-term effects are much less clear. Despite this, there is evidence for changes in neurocognitive functioning (De Beaumont, et. al, 2009), brain function (Breedlove, et. al, 2012), neuroelectrical activity (Pontifex, O'Connor, Broglio, & Hillman, 2009), and motor control (Sosnoff, Broglio, Shin, & Ferrara, 2011). Many studies have examined the long-term effects of concussion with results that show the prevalence of long lasting changes and damage. Several studies demonstrated a potential link between cumulative concussive and sub-concussive events (any blow or impact to the head that did not result in any symptoms; Stephens, Rutherford, Potter, & Fernie, 2005) and depression (Guskiewicz, et. al, 2007), cognitive impairment (Pontifex, O'Connor, Broglio, & Hillman, 2009), and chronic traumatic encephalopathy (neurodegeneration; Gavett, Stern, & McKee, 2011). Individuals with a history of concussion also display a decrease in postural control that mirrors changes seen in older adults, including an increased risk of falls and an altered gait cycle, with greater time spent in a double leg stance phase and less time spent in a single leg stance phase (Broglio & Martini, 2016). These studies help to show that while we may not fully understand the complexity and extent of the long-term consequences of concussions, consequences do exist and may cause complications later in life.

Not only is it important to understand that concussions pose a serious concern in the medical community, but it is also imperative to be aware of the prevalence of concussion in athletics. Sports related concussion accounted for 6.2% of all injuries reported to the NCAA. Women's soccer reported the third highest incidence percentage (8.1%), and the highest among female sports (with football having the highest incidence and men's ice hockey having the second highest; Zuckerman, et. al., 2015). While male sports account for the highest and second highest incidence, females are 1.4 times more likely to report a concussion than males (Covassin, Moran, & Elbin, 2016). Additionally, concussions are the third most common type of injury in women's soccer, making up 8.6% of all injuries, with a rate of 1.42/1,000 athlete-exposures (the number of practices and games for every athlete measured; Dick, Putukian, Agel, Evans, & Marshall, 2007). Furthermore, while all female soccer players have a chance of sustaining a concussion due to the nature of the sport, defenders and goalies are at even greater risk of concussion (Maher, Hutchison, Cusimano, Comper, & Schweizer, 2014).

Soccer poses another unique consideration when discussing head injuries. In soccer, the players are permitted to use their head to strike the ball, this is called a header, or heading the ball. Headers in soccer have been considered a sub-concussive head impact (Di Virgilio, et. al., 2016). Because of the repeated nature of these sub-concussive events in soccer, there is both an interest in and need for additional research on the effects of repeated sub-concussive head impacts on the brain. Current research on sub-concussive impacts in soccer are equivocal. One research study showed a decrease in both short and long-term memory in amateur female soccer athletes after just 20 headers when compared to a control group. These cognitive changes normalized within 24 hours of the heading session (Di Virgilio, et. al., 2016). Another research study documented a transient reduction in the complexity of anterior-posterior (AP) and medial-lateral (ML) postural sway (Haran, Tierney, Wright, Keshner, & Silter, 2013). Alternately, some research has shown no measurable changes in neuropsychological test scores or neurocognitive performance following heading (Stephens, Rutherford, Potter, & Fernie, 2005; Kontos, Dolese, Elbin III, Covassin, & Warren, 2011).

Typical tests used to evaluate cognitive and motor impairment following concussion are static in nature. For example, the Balance Error Scoring System (BESS) test measures how many times the individual moves from the starting position while attempting to stand still (Zimmer, Piecora, Schuster, & Webbe, 2013). These static assessments do not account for *how* an individual moves over time. Incorporating nonlinear tests that measure the quality as well as quantity of motion poses potential benefits including greater sensitivity in detecting potential impairment (Stergiou & Decker, 2011). Thus, research on behaviors that change over time, such as postural sway and visual-motor tracking have surfaced. Nonlinear analyses have been used to evaluate movements, such as postural sway and deviation from a target during visual-motor tracking (e.g., Sosnoff, Broglio, Shin, & Ferrara, 2011; Studenka & Raikes, 2018). These tests focus on the components of the movement patterns the individual is creating instead of simply relying on the average of performance over time.

The visual-motor tracking task requires a participant to sit in front of a computer screen and press on a force sensor or lever. A target, such as a sine wave, is displayed on the screen in front of the participant, and the task is to press with a force that matches the target. Each trial typically takes around 20 seconds to complete and is sampled at around 250 hz, yielding ample samples of data for analysis of non-linear structure (Yentes, Hunt, Schmid, Kaipust, & McGarth, 2013).

When evaluating visual-motor tracking, two common measures of performance are the root mean squared error (RMSE) and the lag. RMSE is defined as the average deviation of the force output from the target signal (see Figure 1; Studenka & Raikes, 2018). Lag is roughly defined as the time difference between the visual display of the force target and the display of the participant's application of force (Fine, et. al, 2016). Lag is approximated by shifting the time series of force back and forth compared to the target signal to find where RMSE is minimal. Both RMSE and lag are expected to increase following a head injury (Studenka & Raikes, 2018; Fine, et. al, 2016).

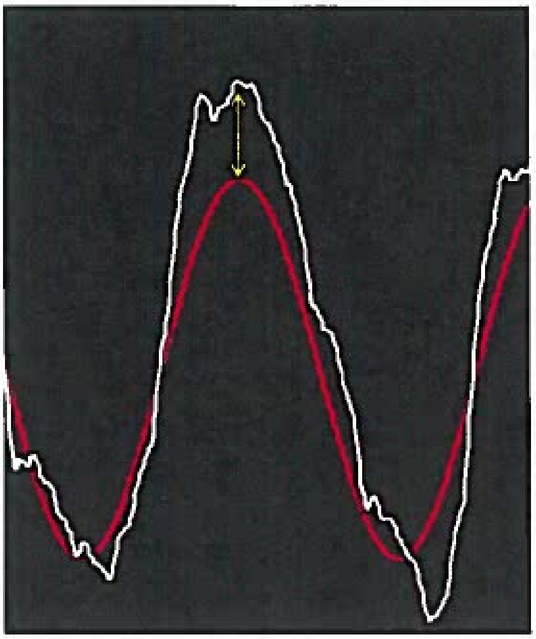

Figure 1. An example of one time point used in the calculation of RMSE. The target force is displayed in red, and the force output is displayed in white.

It is important to not only evaluate the degree of error, but also to determine the movement pattern. Two common mathematical algorithms that measure the repeatability or predictability within a time series are approximate entropy (ApEn) and sample entropy (SampEn). Entropy quantifies fluctuations in movement variability over time. ApEn assesses the probability that points on the time series that are close together, remain close together when another time point is added. SampEn is very similar to ApEn, but was designed to be more consistent than ApEn and be independent of data length. With both algorithms, the smaller the entropy number, the more regularity present in the movement pattern (see Figure 2; Yentes, Hunt, Schmid, Kaipust, & McGarth, 2013).

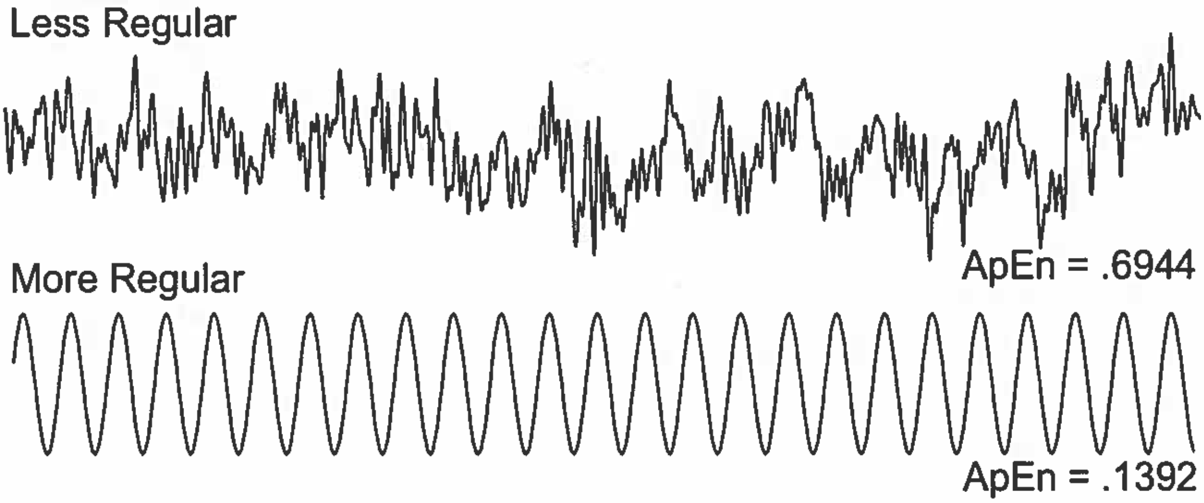

Figure 2. An example of two waveforms with corresponding ApEn values.

Current research has shown notable differences in the non-linear structure of postural sway both pre-and post-concussion and in concussed individuals when compared to a control group. Immediately following concussion, postural sway became more regular (lower ApEn; Cavanaugh, et. al, 2005; Cavanaugh et. al, 2006; Sosnoff, Broglio, Shin, & Ferrara, 2011). These impairments lasted longer than 3-4 days, despite the athletes having no apparent symptoms of unsteadiness (Cavanaugh, et. al, 2006). In addition, Broglio & Martini (2016) have shown long term impairments in postural sway, including a reduction in the complexity of ML sway in patients who had suffered a concussion when compared to a control group.

In addition to postural sway, visual-motor tracking has been examined in individuals with previous history of concussion. While the literature is limited, there is evidence that individuals with previous history of concussion show more regular visual-motor tracking. Additionally, females with a history of two or more concussions exhibited more regularity (SampEn) in motor output on a visual-motor tracking task requiring them to maintain index finger pressure on a load cell, compared to females with a history of one or no concussions (Studenka & Raikes, 2018).

Studenka & Raikes' (2018) findings showed significant differences between females with a history of multiple concussions compared to those without, which suggested that females may be more susceptible than males to long-term effects of concussion. In addition to these findings, there is evidence that, following concussion, females tend to score lower on neurocognitive tests when compared to their male counterparts (Sandel, Schatz, Goldberg, & Lazar, 2016; Colvin, et. al, 2009). Gender differences have also been seen with respect to memory following concussion. Males performed better on attention and visual memory tasks compared to females, while females performed better on verbal-list learning and executive functioning compared to males (Moore, Ashman, Cantor, Krinick, & Spielman, 2010). Female soccer players also had greater time loss from participation after a concussion occurring in practice compared to males (Covassin, Moran, & Elbin, 2016). This evidence supports differences between men and women regarding effects of and recovery from concussion. It may also be the case that sub-concussive events impact women differently than men.

Based on emerging research of the acute effect of headers on brain health, the main aim of this study was to examine the influence of a heading drill on the visual-motor behavior of a group of NCAA female soccer players. We hypothesized that, post-drill, performance on the visual-motor tracking task in all conditions would worsen and that visual motor tracking would exhibit greater regularity. We further hypothesized that, following the heading drill, we would see greater visual-motor lag during the visual motor tracking of an irregular wave form. In particular, we hypothesized greater lag in a condition where less visual information about the future state of the waveform was available.

Method

Participants

Thirty-one women from a Division I, collegiate women's soccer team were recruited to participate. We excluded 5 goalkeepers because they typically do not participate in heading drills and their practice differs from that of the rest of the team. We also excluded any athlete with an injury or illness that prevented them from fully participating in practice. Of the 20 remaining participants, 9 were able to complete all sessions for both conditions. Included in these 9 participants were two defenders, one participant who played both defense and midfield, five midfielders, and one forward. The mean age of the participants was 19.22 (SD = 1.30) years old. The participants had been playing soccer for an average of 13.67 (SD = 2.06) years and had been playing for their current collegiate team for an average of 1.44 (SD = 1.59) years. Of the 9 participants, five had a previous history of a concussion, three with one prior concussion and two with two prior concussions. A between-participants design would have yielded too few participants for comparison, and therefore, we measured visual-motor tracking for all participants before and after two different practice sessions, one with and one without headers.

Apparatus and Task

The tracking device consisted of two main components: the computer and the force sensor (ATI Industrial Automation force sensor, diameter 1.27 cm; Apex, NC). The computer screen displayed the target waveform as well as a representation of the force captured by the force sensor. The force from the sensor was amplified via a National Instruments DAQ board (National Instruments, Austin, TX). The target line was displayed in red against a black screen and the participant's force was displayed as a white line. The amount of pressure required was relative to the participant. Each participant began the task by applying maximal force to the force sensor. The pressure required for the remaining trials was set at 10% of the participant's maximal force. The force sensor faced to the right, and was centered in front of the computer screen, and affixed to a wooden block (see Figure 3).

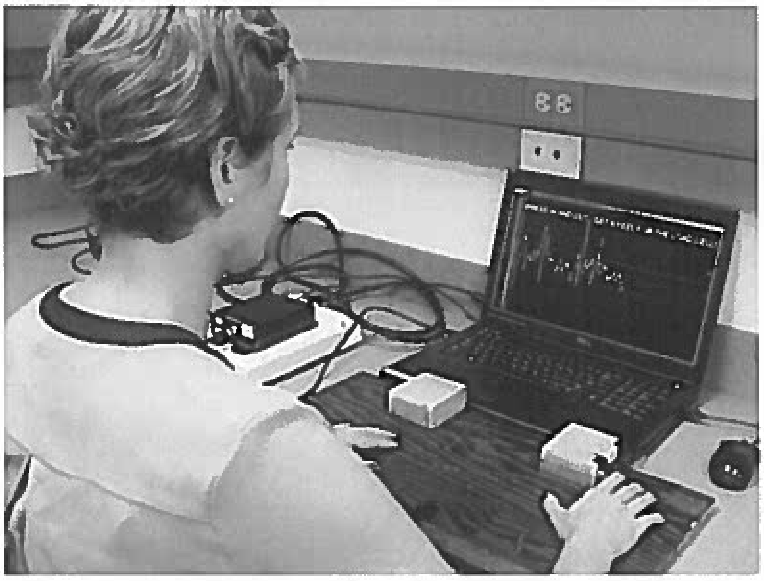

Figure 3. A participant performing the visual-motor tracking task.

Each testing session consisted of three conditions. A participant completed a practice trial and then five testing trials for each condition. Each trial lasted 20 seconds. The first 3 and last 2 seconds of each trial were discarded; seconds 3 through 18 were used for analysis. The first condition was a line representing a constant force target that a participant attempted to trace (see Figure 4a). The second condition was a brown noise waveform. This waveform was used to examine how the participant's movement patterns adapted to a changing environment (Figure 4b). The brown noise waveform was semi-structured, but also had sufficient fluctuation to allow for assessment of visual-motor lag. The third condition was a brown noise waveform with only 300 ms of visual information displayed in advance of when the participant was required to match the line (Figure 4c). This visual information condition was used to examine how participants used limited visual information to adapt to a changing environment (300 ms is slightly longer than standard reaction time). On each trial, a different iteration of a brown noise waveform was displayed. The brown noise waveforms were created in advance of the study by creating random estimates of the power from 0-70 Hz in the frequency domain. New waveforms were generated using different seed values for the randomization. Power estimates were scaled to have a spectral slope of -2. The waveforms were then filtered using a Butterworth cutoff filter at 12 Hz. This filtered power spectrum was then inverse Fourier transformed back to the time domain producing the target waveform.

This waveform was cropped to span 20 s and scaled to have a mean of 10% MVC and to vary from 5-15% MVC. Each 20 s waveform used exhibited a spectral slope of -1.9 and -2.1.

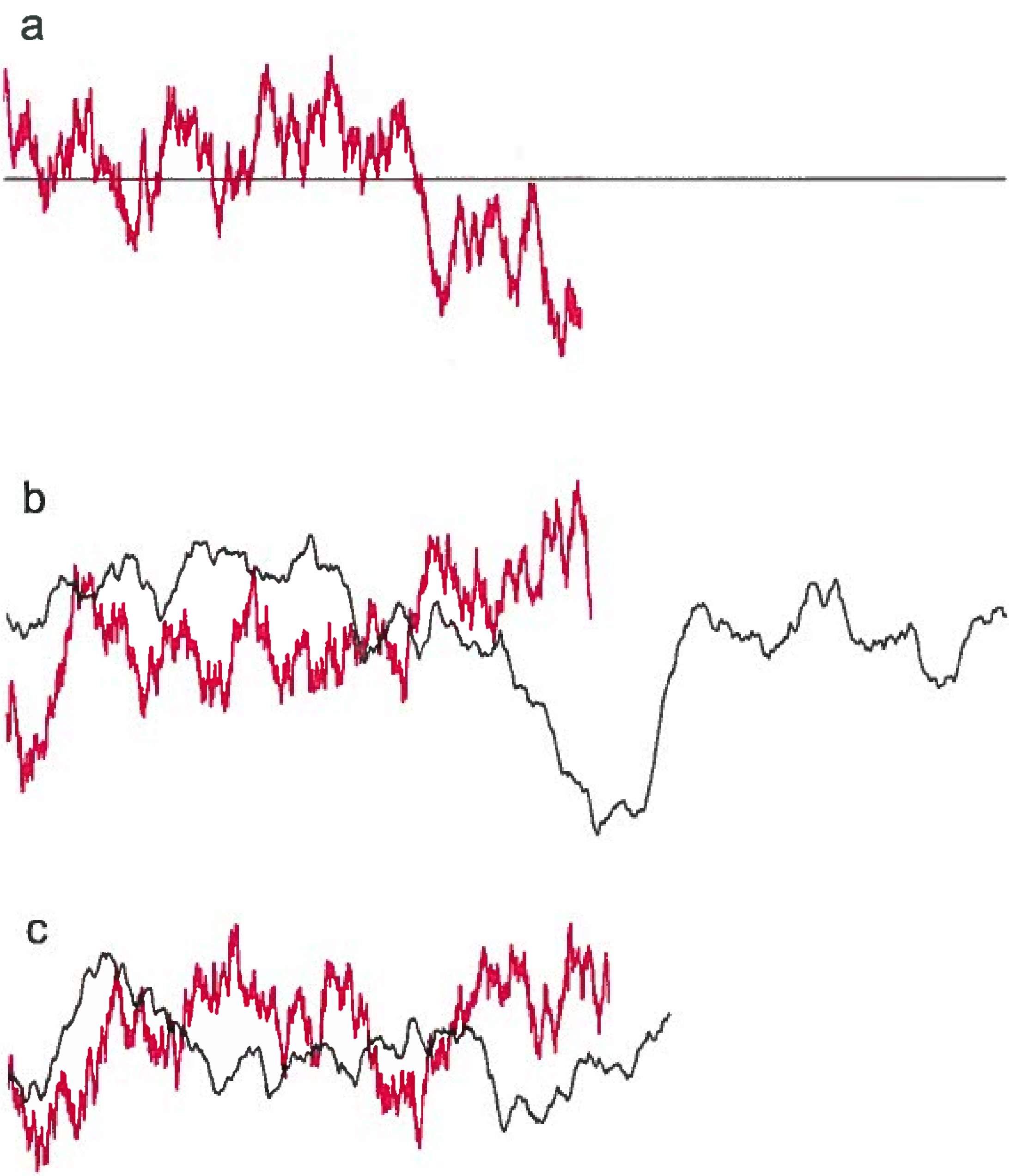

Figure 4. Examples of the isometric force task. The constant force waveform (a), the brown noise waveform with full visual information (b), and the brown noise waveform with only 300 ms of visual information (c). The red line represents a participant's force, the black line is the target she was trying to trace.

Procedures

Each participant acted as her own control. Every participant reported for two rounds of three sessions of testing: a pre-practice testing session, a post-practice session, and a 24-hour follow up session (see Table 1). We chose to include the 24-hour follow up session because there is research that alterations seen after headers normalized 24 hours (Di Virgilio, et. al., 2016). Each participant read and signed an informed consent form approved by the University IRB prior to beginning any testing. Each round of testing was completed over two days. For the first session, participants performed testing before and following a typical practice with no headers. This session was completed at the beginning of the season, and no headers had yet been performed during the team practices. Participants returned one week later to complete the three experimental sessions pre, post, and 24 hours post practice that involved headers. The headers were performed as the last drill before participants performed the post-test. Prior to testing, participants filled out a questionnaire, including questions pertaining to basic information such as age, position, and years of playing soccer, as well as questions addressing the participants' previous history of concussion. Once the participant finished the questionnaire, she completed the visual motor tracking task. This task consisted of each participant placing the lateral side of the second digit of her right hand on a force sensor. The participant then abducted her second digit against the force sensor. The computer screen displayed a line that the participant was instructed to trace by adjusting the pressure of her finger contraction as it abducted against the force sensor (see Figure 3). The greater the force allied to the force sensor, the higher the output line on the computer screen traveled. The output from this task was a time series of continuous behavior that allowed for the analysis of movement patterns over time.

After the completion of the visual-motor tracking task, for both the control and experimental sessions, the participants completed a coach-run soccer practice. At the end of the practice for the experimental phase, participants completed a heading progression drill. This drill included 40 headers, starting with the participant sitting on the ground for 10 headers, then kneeling for 10 headers, then standing for 10 headers, and concluding with 10 jumping headers. All balls were hand tossed to the participant by a teammate. After practice, the participants completed the visual-motor tracking task again (two at a time at 10-minute intervals). The participants then came in 24 hours after the second testing session to complete the final session of force tracking.

NO HEADERS									
Session	Pre			Post			24 hr. Post		
Condition	1	2	3	1	2	3	1	2	3
Trial	1,2,3,4,5	1,2,3,4,5	1,2,3,4,5	1,2,3,4,5	1,2,3,4,5	1,2,3,4,5	1,2,3,4,5	1,2,3,4,5	1,2,3,4,5
HEADERS									
Session	Pre			Post			24 hr. Post		
Condition	1	2	3	1	2	3	1	2	3
Trial	1,2,3,4,5	1,2,3,4,5	1,2,3,4,5	1,2,3,4,5	1,2,3,4,5	1,2,3,4,5	1,2,3,4,5	1,2,3,4,5	1,2,3,4,5

Table 1. Design of study. Two testing blocks (no heading and heading). In each, three sessions, three conditions within each session, and five trials within each condition.

Statistical Analysis

Analysis was run using three dependent variables, the root mean squared error (RMSE), the lag between the visual stimulus and the motor output, and the regularity (SampEn) of the motor output. A 2 factor ANOVA with within subject factors; condition (headers, no headers) and session (pre, post, 24-hour post) was run for the straight-line waveform. A 3 factor ANOVA was run on the brown noise waveforms as our main objective for including these was to be able to compare performance with varying levels of visual information. This within-subjects ANOVA included 2 waveforms (full visual, limited visual), 2 conditions (headers, no headers) and three sessions (pre, post, 24-hour post).

Results

Overall Performance

In order to assess overall performance on visual-motor tracking, we examined the normalized (mean difference divided by the range) root mean squared error (RMSE) of each participant's force output compared to the goal waveform. Typically, with repeated trials (practice), performance improves. We first wanted to examine specific learning effects for all three conditions. In order to capture the largest effects of learning, we examined performance on the first trial of each session within each condition, for each waveform using ANOVAs, described above.

For all waveforms, RMSE decreased over time (see Figure 5). The session with headers (performed following the session without headers; *Mean (M)* = .58, *Standard Deviation (SD)* = .25; *M* = .70, *SD* = .29) exhibited significantly lower RMSE than the session without headers (*M* = 1.02, *SD* = .45; *M* = 1.12, *SD* = .45) for both the straight line and the brown noise waveforms respectively. This is indicated by a significant session main effect for the Straight-Line waveform ANOVA, $F\ (1, 8) = 24.42, p = .001, \eta_p{}^2 = .75$, as well as the Brown Noise waveform ANOVA, $F\ (1, 8) = 38.18, p = .0003, \eta_p{}^2 = .78$. For the Straight-Line waveform, no significant condition effect, $F\ (2, 16) = 2.36, p = .13$, or condition by session interaction, $F\ (2, 16) = 2.98, p = .08$, was seen. For the Brown Noise waveforms, a significant condition effect was seen, $F\ (2, 16) = 7.28, p = .006, \eta_p{}^2 = .33$. A significant session by condition interaction, $F\ (2, 16) = 4.67, p = .03, \eta_p{}^2 = .43$, supported a decrease in RMSE over the three conditions of the first session, but not over the three conditions of the second session. A significant session by wave interaction, $F\ (1, 8) = 11.12, p = .01, \eta_p{}^2 = .24$, indicating slightly better performance for the full signal waveform during session two.

Our main hypothesis was that performance would decrease following a session of headers versus following soccer practice with no heading practice. Because we had all participants perform practice with no headers prior to practice with headers, we could not directly compare the post practice values between sessions. We, therefore, calculated a projected value for post-header practice based on the learning curve from all conditions in session 1 and the first condition in session two for each participant, and compared the projected post-header value with the actual post-header value of RMSE (see dotted bars in Figure 5). The projected next value was calculated using the interp1 function in Matlab (The Math Works, Inc., Natick, MA) and linear extrapolation specified. Paired, two tailed t-tests were performed to compare the projected and actual values for each waveform. The actual value of RMSE for the Straight-Line waveform (*M* = .66, *SD* = .26) was significantly greater than the projected value (*M* = .31, *SD* = .32, *t* (8) = -2.4, *p* = .05, *d* = .80), indicating that performance in visual-motor tracking was impaired following performance of headers in practice. The actual value of RMSE for the Brown Noise full vision waveform (*M* = .64, *SD* = .18) was significantly greater than the projected value, (*M* = .32, *SD* = .09, *t* (8) = -4.3, *p* = .003, *d* = 1.36. The projected (*M* = .67, *SD* = .38) and actual values (*M* = .74, *SD* = .16) of RMSE for the Brown Noise, 300 ms vision condition were not significantly different, *t* (8) = -.4, *p* = .67, *d* = .16.

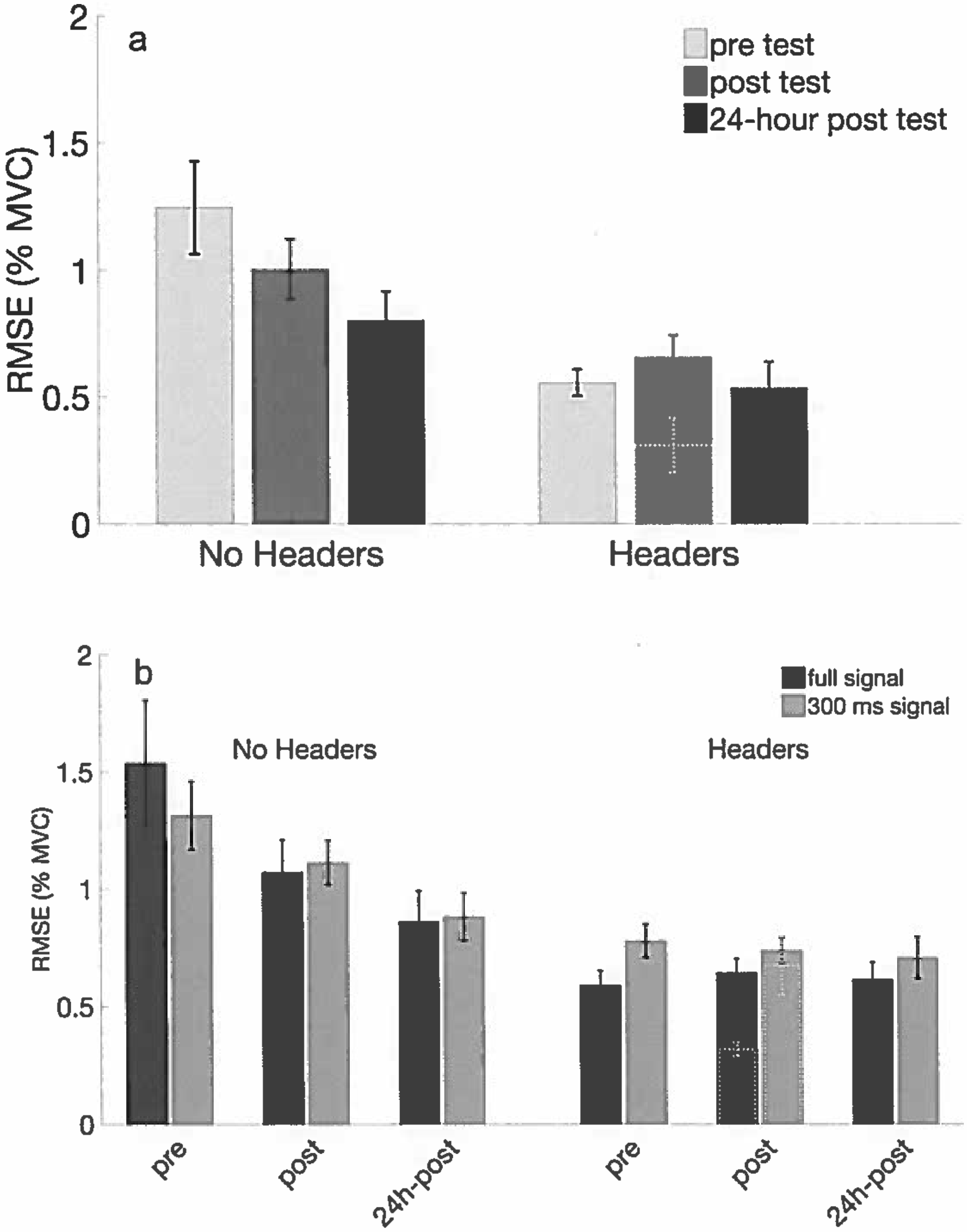

Figure 5. RMSE for the first trial of each testing session for the straight line (a), and brown noise (b) waveforms in both sessions, pre, post and 24 hours post soccer practice, with the projected value displayed as white dotted lines.

In addition to overall performance changes, we hypothesized that the structure of force variability would be influenced by performance of headers. The change in force production structure was assessed using the dependent variable of Sample Entropy. Because we were not interested in how SampEn changed over time (e.g., was learned), but rather, how values of SampEn might change following headers, the average of the 5 experimental trials was evaluated for each condition. No main effects or interactions were seen for the Straight-line waveform or for the Brown Noise waveforms ANOVA (see Figure 6). As this is the first study, to our knowledge, that has examined potential change in non-linear aspects of behavior following a series of sub-concussive events, we offer up a power analysis to determine potential sample size needed for follow up study. Effect size of our sample for the interaction between condition and session, alpha of .05, and Power of .8 was used to calculate total sample size needed to show a significant difference between pre and post header Sample Entropy scores. G*Power (Faul et al., 2007) indicated that a total sample size of 34 would be needed to accurately detect differences between pre and post headers given the effect size.

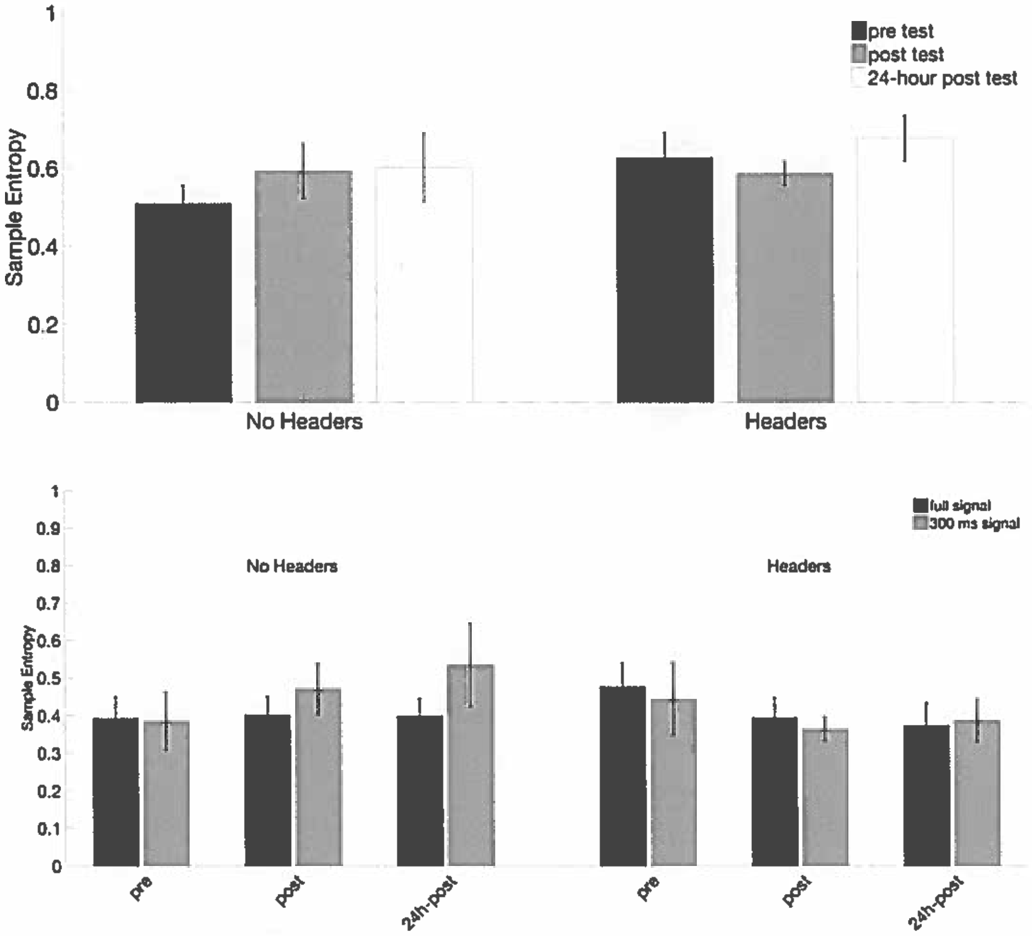

Figure 6. Sample Entropy average over 5 trials for the straight-line waveform (top graph) and the brown noise waveforms (bottom graph).

The Role of Visual Information

Our second aim was to examine changes in the processing of visual information following the heading drill. We hypothesized that, following the heading drill, we would see greater visual-motor lag, and, in particular, a greater lag when less visual information about the future state of the waveform was available. We ran a three-way, within-subjects, ANOVA with condition (headers, no headers), session (pre, post, 24-hour post), and waveform (full vs. 300 ms) for the dependent variables of lead/lag and correlation coefficient between the goal waveform and the waveform produced by participants.

The only significant main effect for lead/lag was seen when comparing the full vision waveform with the limited vision waveform, *F* (1, 8) = 8.20, *p* = .02, indicating greater lag for tracking a signal with limited visual information. No other main effects or interactions were found (see Figure 7).

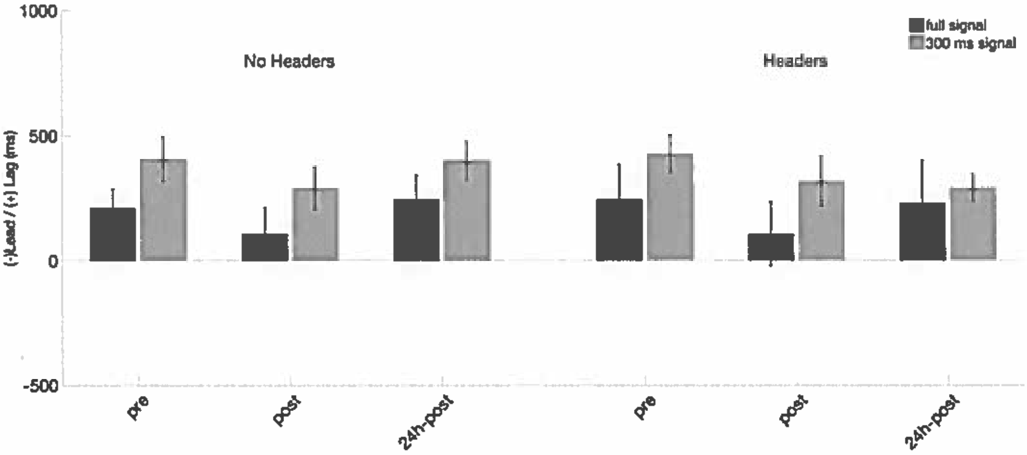

Figure 7. Lead/lag values for both brown noise waveforms for sessions with and without headers pre, post and 24 hours post soccer practice.

Discussion

In our first hypothesis, we predicted that there would be a decrease in performance (increase in RMSE), and an overall increase in the regularity of the structure of visual motor tracking (SampEn) directly following performance of headers. This hypothesis was partially supported. Based on a projected value of RMSE, performance did decrease immediately following headers, which indicates an influence of heading during practice. This change is comparable to the effect seen in short term sleep deprivation (<45 hours) when completing a simple motor task (Pilcher & Huffcutt, 1996). Additionally, Haran, et. al (2013) provided evidence that soccer headers caused changes in postural stability, including an increase in ML and AP sway. Although postural sway and visual-motor tracking are not identical, they both detect small motor pattern changes and both hinge on the complex sensory-to-motor transformation, which are often overlooked with the standard concussion testing protocol.

While increased RMSE was seen following headers, as hypothesized, there was no significant change in regularity of the movement structure. This may be due to the limited number of headers taken by the participants or the amount of impact of the headers. While research indicates that non-linear aspects of motor behavior may change following concussion (Broglio & Martini, 2016; Studenka & Raikes, 2018), there is still a need for research regarding impact on motor behavior directly following sub-concussive events. While some research indicates impairment following performance of headers, including a decrease in both short and long-term memory and a reduction in AP and ML sway (Di Virgilio, et. al., 2016; Haran, Tierney, Wright, Keshner, & Silter, 2013), we provide no additional evidence of changes in movement structure following soccer heading.

Due to studies indicating a decrease in visual-motor control following concussion, our second hypothesis was that, following headers, there would be an increase in lag between the visual stimulus and the force output positions. We predicted that this lag would be greater for tracking the signal with limited visual information (300 ms). Fine, et al. (2016) showed significant increases in velocity error between individuals with a history of concussion compared to controls when using a hand grip dynamometer on an unpredictable tracking task. They also found a slight increase in lag for the participants with a history of a concussion in both predictable and unpredictable tasks compared to controls. In this study, while greater lag was seen for the condition with limited visual information compared to full information, there was no significant change in lag following headers for either the full or the limited visual information sessions. Although there is limited research on the influence of sub-concussive events on visual-motor control, there is evidence that vergence (simultaneous movement of both eyes in opposite directions) can be affected by concussion. This deficit is often temporary and can be treated with vision therapy but can affect an individual's activities of daily living while they are experiencing compromised visual control (Thiagarajan, Ciuffreda, & Ludlam, 2011). The limited number of participants, limited number of headers, amount of impact of the headers, and the delay in testing some of the participants (only two could be tested every 10 minutes), could all have influenced the lack of findings regarding lag.

This preliminary research shows that, while changes in visual motor tracking are limited following sub-concussive events, they are still detectable, at least immediately following performance of headers. These performance decrements also resolved within 24 hours. No long or short-term change in the non-linear structure of movement was detected. Based on our limited sample size and other research indicating long-term impairment in the non-linear structure of motor output following *concussive* events, we suggest that detection of subtle, non-linear changes in motor process (as measured by Sample Entropy) are smaller and may require larger samples than changes in motor output (e.g., RMSE).

Conclusions

Due to the postulated decrement in performance immediately following headers, it might be appropriate to avoid soccer heading drills within 24 hours of competition. Additionally, clinicians might think about accounting for the drills completed during practice when evaluating a potentially concussed athlete, as minor changes may be due to headers in addition to any impact to the head that resulted in concussion symptoms.

Limitations

Due to the availability of a single soccer team and a limited number of participants within the team that met our inclusion criteria, the sample size for this study was small. Because of this small sample size, we were only able to have one group instead of using an experimental and a control group, disallowing for the direct comparison of headers separate from learning. This also forced us to create a projected value post headers. While the projected values afforded us the ability to compare at a theoretical level, it does not account for any potential plateau in learning. Due to equipment limitations, we were only able to test two participants at a time, which meant that some participants waited longer to be tested post-practice than others. Therefore, we were unable to obtain data immediately post-practice for the majority of participants. The number of headers could be another limitation; however, this heading drill is one typically used during practice. By testing participants after actual practice sessions and using a drill already employed by their coach, we were able to examine athletes within their normal environment, which increased our external validity.

Future research should include a larger sample size, separate experimental and control groups (which would eliminate the need for a projected value), and more immediate post-practice testing. Additionally, more detailed measurement of sub-concussive events throughout the season including measurement of exact forces delivered to the ball during headers would bolster findings and implications of research on the impact of sub-concussive events both on linear and non-linear aspects of cognition and behavior.

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