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Introductory statement for *The Journal of Sport and Exercise Science* special issue: Skill acquisition – research and practice

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Skill acquisition, as a subdiscipline of sport and exercise science, is broad and multidisciplinary. It encompasses motor learning, motor control, neuroscience, the study of expertise, sport and exercise psychology, and crosses over into other exercise science fields of research like strength and conditioning, biomechanics and exercise prescription. As the subdiscipline has evolved, a number of so-called parent disciplines have been represented, ranging from Education and Physical Education, to Psychology, and Physiology (neuropsychology and neurophysiology). The emphasis on other complementary subdisciplines has also evolved to contemporary areas, such as data analytics and computer science. As such, defining the impact that skill acquisition researchers have in the broader sport and exercise landscape can be difficult. Furthermore, some of the fundamental concepts related to any field of study within sport and exercise, such as transferability of practice, practice design and the relationship between feedback and performance, have all been discussed extensively in skill acquisition research. It is, therefore, clear that despite being considered a separate subdiscipline, skill acquisition scientists' research extends into other sport and exercise science subdisciplines.

As a result of this diversity of disciplines represented in the skill acquisition area of research, the dissemination of research findings is often dispersed over different mediums, from coaching handbooks and blogs, to peer-reviewed international publications in scientific journals from a variety of research domains and disciplines. However, there is currently no skill acquisition specific journal that researchers can use to publish the findings of their studies. This often makes it difficult for skill acquisition researchers to build on existing research evidence, and for practitioners to find evidence that can inform best practice. In fact, in a study published in the Journal of Strength and Conditioning Research, Fullagar and colleagues (Fullagar, Harper et al., 2019) asked 67 United States practitioners about their perspectives on evidence-based practice in sport. Interestingly, when asked about the degree to which they perceived that the contribution of sport science outweighs that of expertise or experience in a variety of research domains, 75% of the research domains that were rated as more informed by personal experience over scientific evidence, commonly fall within the domain of skill acquisition research (i.e., mental training and preparation, tactical/strategical components of performance, talent development/recruiting). Additionally, Fullagar, McCall et al. (2019) reviewed current perceptions of practitioners, researchers and coaches in sport. The respondents indicated that "knowing how to coach", "participant and athlete needs", and "skill acquisition" are areas of research that can directly benefit coaching practice. Moreover, when Steele et al. (2014) sought to understand the underuse of skill acquisition specialists, they revealed a lack of understanding of the role by pre-elite and elite coaches and athletes. Since that time, when participants reported few experienced skill acquisition specialists in applied fields, anecdotal evidence suggests that there has been a modest increase in the number of experienced and well-trained practitioners in a range of professional and Olympic and Paralympic sports. However, the visibility issue in this subdiscipline still persists.

While skill acquisition research is abundant, it does not seem to be available to the same degree as research in other domains of sport and exercise science. In a modest attempt to address some of these challenges, the Australasian Skill Acquisition Research Group (ASARG) was founded in 2007 to unite skill acquisition researchers in the Australia-Pacific region and to provide a platform for aspiring undergraduate and postgraduate students and sport, exercise, and health practitioners. Since then, the group has held meetings every year and its following has expanded and broadened to incorporate a varied practitioner base interested in furthering their understanding and application of skill acquisition knowledge. To reflect the increasing reach and inclusive nature of the group, ASARG was renamed ASAN in 2017, the Australasian Skill Acquisition Network.

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This special issue stems from the 13th meeting of ASAN in Hamilton, New Zealand, at the University of Waikato in November 2019. This special issue highlights the breadth of research and healthy state of the subdiscipline in the region. The issue includes research on motor control during a jumping task in injury-prone patients (Hanzlíková, Masters, & Hébert-Losier 2020), neuropsychological function in athletes who had sustained a concussion at elevation (Treacy & Heflin, 2020), the degree to which motor learning in a golf-putting task can be affected by the performance of a hand contraction task (Hoskens et al., 2020), the influence of apparel colour on self-perceived and actual kicking performance (Kam et al., 2020), the relationship between coach instructions and decision-making in football players (Beavan & Fransen, 2020), the influence of a neurofeedback intervention on decision-making when stopping penalties (Pillai, Blanchfield, & Cooke, 2020), the degree to which music can elicit enduring positive affective states in footballers (McGuckian & Pepping, 2020), how normalised brake work algorithms can be used to analyse mountain biking performance (Miller & Fink, 2020), and what training professional esports players engage in before competing in a major international tournament (Pluss et al., 2020).

Collectively, these studies provide a good overview of current topics that are of interest to Australasian Skill Acquisition research, as well as display the broad skill set and interests that these researchers possess. We hope you enjoy this special issue, that you find value in its contents, and that the studies included in this special issue both guide and inspire you to further propel our field into the spotlight.

Finally, we would like to thank the authors for their work during what was a challenging period globally, due to the COVID-19 pandemic, which also unfortunately led to the first cancellation in the history of ASARG/ASAN meetings. We particularly thank our reviewers, who were instrumental in the process of pulling together this special issue, and mostly drawn from the ASAN membership. This collaboration bodes well for the continued strength and collegiality of the network.

Guest Editors,

Job, Gert-Jan and Clare

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The influence of coaching instructions on decision-making in soccer

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ABSTRACT

This experimental study examined if precueing influences soccer players' (N = 13, age = 19.5 ± 2.2 years) decisions and visual search behaviour in a soccer-specific video-based decision-making task. The decision-making task was preceded by a video containing either the basic rules of soccer (neutral condition) or specific coaching instructions that were either compatible or incompatible with the correct decision of the 30 subsequent clips (precue condition). Overall, decision-making accuracy (80.81 ± 8.40 %) was lower and response time (590.75 ± 203.47 ms) was faster in the precue condition compared to the neutral condition (85.85 ± 4.41 %; 630.47 ± 241.55 ms). Additionally, fixation location appeared to be marginally influenced by the compatibility of the precues given. This research supports the conclusion that compatible precues improve sport specific decision-making while incompatible precues hinder performance. Coaches with experienced athletes are advised to use a more implicit approach to allow players to optimize their decision-making and not constrain athletes' perception of environmental cues.

1. Introduction

It is common for athletes from different domains to receive tactical guidelines, instructions and/or feedback from their coach aimed at enhancing performance (Porter, Wu, & Partridge, 2010). Seemingly, a large body of instruction-related research has investigated whether an explicit (i.e., consciously clear and obvious) or an implicit (i.e., a not-obvious and more reliance on self-discovery) method is better for facilitating the acquisition of perceptual-cognitive skill in an athletic population. Research has demonstrated that the positive effects of explicit instructions seem to have an inverse relationship with an increase in experience, as explicitly instructing experienced athletes has been reported to be detrimental to sporting-performance (Buszard, Farrow, & Kemp, 2013). Accordingly, there is a greater advocacy for more implicit means of delivering instructions with experienced athletic populations. Allowing the participant to discover for themselves the relationships between cues/movement patterns and behavioural outcomes has been well documented to enhance perceptual-cognitive skills (Farrow & Abernethy, 2002; Kirlik, Walker, Fisk, & Nagel, 1996; Williams, Ward, Knowles, & Smeeton, 2002). Such research on how humans effectively interact with their environment is related to either the Information Processing Approach (Fitts & Posner, 1967; Schmidt, 1975) or the Ecological Approach (Turvey, 1977; Turvey, Shaw, Reed, & Mace, 1981) whereas research that adopts the theory of *priming* to explain the coupling of perception and action has largely remained in cognitive psychology literature.

Priming is an interesting paradigm to explain motor behaviour in sport because it focuses on the alteration in behaviour based on being subjected to previous stimuli (Elliott, 2004; Posner, Nissen, & Ogden, 1978). One common method to prime participants is known as precueing (Posner et al., 1978). A precue is defined as a stimulus provided to the participant prior to the task that offers them a hint as to what may occur next. Precueing is also a technique that many coaches use to deliver their instructions to athletes in order to encourage desired tactical responses (Farrow & Abernethy, 2002). For example, coaches may deliver probabilistic information about the opposition's tactics before the match, such as telling a tennis athlete that '75 percent of the time, the opponent serves more to the right'. Together, the similar incentives of both precueing techniques and instruction-related research is to further understand what transpires when an individual's attention is directed to a certain part of the environment by a cue, and how it impacts on the decision-making and motor behaviour of an individual.

Beavan et al. (2019) further demonstrated that implicit precues could either enhance or hinder the response times of highly

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talented youth football players based off the congruency of the delivered precue in a four-choice response time task. Advanced information was presented about the likely location of the upcoming stimulus, and players had to respond accordingly. The findings demonstrated that stimulus detection and response times were enhanced when athletes were provided with a precue that contained correct and beneficial information for the subsequent task (i.e., a congruent precue); confirming the results from the original study in a general population (Posner, Snyder, & Davidson, 1980). Opposingly, when the precue provided misleading or incorrect information before the subsequent task (i.e., an incongruent precue), it hindered athletes' response initiation times. This demonstrates that experienced athletes are able to act upon beneficial information, but are still susceptible to misleading information delaying their response times. However, as the results from Beavan et al. (2019) were based on simple motor responses, the authors advocated for such precueing paradigms to be further used in more ecologically valid environments to improve our understanding of how advanced information can alter the perception-action coupling of athletes and more complex sport specific movements.

In the same way, a coach's instructions may either be congruent or incongruent with a situation players may encounter during a game. For example, a soccer coach may instruct a team to maintain possession of the ball in central regions of the pitch to improve the likelihood of more shots on goal. If a situation arises during the game in which there is an available teammate who is in a position located centrally on the field, the precue (i.e., a coach's instruction) is congruent with the provided scenario, and in-turn the athlete may have a faster response time to act upon this decision. However, if a situation occurs where there are no good passing options to keep the ball central, the player may be forced to search for an option that is incongruent with the instructions; leading to an alternate decision being made (or having to disobey instructions) by passing to a player wider on the field that is more available. This may result in slower response times. It is therefore plausible that coaching instructions may alter a player's attention to different in-game cues, resulting in different information perceived and consequently a possible change of sporting behaviour (Buszard et al., 2013). Accordingly, the associated impact from tactical instructions on the decision-making process of an athlete may be similar to what has previously been demonstrated in precueing laboratory studies (Posner et al., 1980; Rosenbaum, 1983).

This alteration in motor behaviour is thought to be attributed to a change in the participant's attention relative to the intention of the precue (Posner et al., 1980); however many priming studies lack the inclusion of attentional measurements to confirm such. Indeed, one study compared the visual search behaviours of athletes under different instructions provided before the task. Buszard et al. (2013) reported that although no differences were found among three instructional groups in mean number of fixations, mean fixation duration and search rate, differences were found between the proportion of total time fixating on specific areas of interest as a result from the intention of the instruction. As a result, the authors concluded that an explicit direction of athletes' attention to certain in-game cues may change the information perceived from the environment, and may be an underlying reason for the negative influence that explicit tactical instructions has on many sporting-performers (Buszard et al., 2013; Memmert & Furley, 2007).

Therefore, the purpose of this study was to investigate the effects of tactical instructions as a form of precueing on measures associated with decision-making (i.e., gaze behaviour, response accuracy and response time) in a soccer specific video-based decision-making task. First, it was hypothesized that players would have poorer decision-making performance when receiving tactical coaching instructions compared to when no precues were provided. Second, it was further hypothesized that congruent precues would enhance decision-making performance while incongruent precues would hinder performance in a video-based decision-making task. Last, due to the intention of the delivered precues (reported below in the methods section), the third hypothesis was that participants would demonstrate a higher proportion of total time visually fixating on defenders and the goalkeeper/net, and a lower proportion on unmarked attackers in the precueing condition compared to the neutral condition.

2. Methods

2.1. Participants

A total of 13 male intermediate soccer players (19.5 $\pm$ 2.2 years) were recruited from several regional soccer clubs, all of whom were midfielders and right footed. Seven of these participants had their eye movements recorded. Participants had an average of 13.4 $\pm$ 2.0 years of experience in soccer and all had normal or corrected to normal vision. Written informed consent or consent from either a parent or guardian if participants were under the age of 18 was received prior to the commencement of this study. Ethical approval was obtained by the local Human Research Ethics Committee.

2.2. Test film

Thirty film based, offensive-play videos previously developed and validated by Vaeyens, Lenoir, Williams, Mazyn, and Philippaerts (2007) were used to assess perceptual-cognitive skill (Figure 1). The videos used in the current study were identical to those used in the original studies (Vaeyens, Lenoir, Williams, Mazyn, et al., 2007; Vaeyens, Lenoir, Williams, & Philippaerts, 2007). Vaeyens and colleagues used a professional cameraman to film the simulations from an elevated perspective (approximately 3 m) in the centre circle area behind one of the attackers. Participants are required to imagine themselves as an offensive midfielder playing in the central position that was just in front of the camera, playing in the yellow vest and was at all times clearly identifiable (i.e., 'yellow player' in Figure 1). The recorded simulations varied in the number of players presented on film: 2 versus 1 (i.e., 2 attackers, including the yellow player, vs. 1 defender), 3 versus 1, 3 versus 2, 4 versus 3, and 5 versus 3. Each condition also included a goalkeeper. Videos lasted an average of 6 s and ranged between 4-9 s. A freeze frame of 1.5 s on the initial scene of each clip allowed participants to identify their teammates and the opposing team, as well as their positions on the field (Roca, Ford, McRobert, & Williams, 2011). Each video clip was occluded using iMovie (10.0.9, Apple Inc., California, USA), indicated by a black screen. The moment of occlusion occurred at the critical decision moment, considered to be the precise moment at which the participant was required to make a decision and execute a response action (Vaeyens, Lenoir, Williams, Mazyn, et al., 2007; Williams et al., 2002). Accordingly, each sequence ended with a pass toward the player wearing the yellow vest. Five experienced soccer coaches independently viewed the offensive simulations to ensure that each sequence was realistic and was representative of actual game play. The presented test films included only the sequences approved by all five coaches, being a total of 30 trials consisting of: four 2 vs.1 (offensive players vs. defensive players), nine 3vs.1, six 3vs.2, five 4vs.3 and six 5vs.3 scenarios.

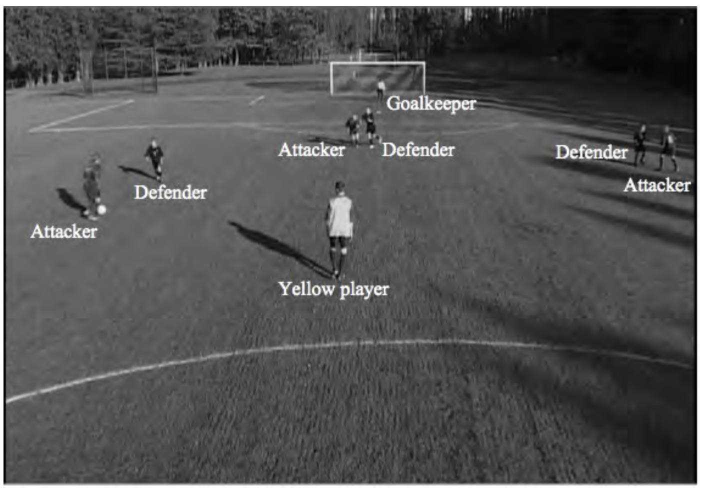

Figure 1: A screenshot of an offensive scenario (Vaeyens, Lenoir, Williams, Mazyn, et al., 2007).

2.3. Precueing and neutral videos

The animated videos were created using VideoScribe (Sparkol, Bristol, England). The precueing video was designed to simulate tactical instructions from a coach typically received before the game or during half time using a whiteboard to display their instructions. The precueing video presented three written phrases with a voice overlay and a diagrammatic representation of the instructions. The precues were as follows: i) “The opposition’s goalkeeper is insecure, so just get a shot in on target whenever you get the chance”, ii) “The opposition’s defenders are fast and strong, but they are not agile. In a one-on-one situation, taking them on is the best choice”, and iii) “In our formation, we outnumber the opposition in the central axis, so avoid using the width of the field”. These three phases were written in appropriate coaching language by an experienced, appropriately qualified coach to ensure the realism of the situations was maintained. Furthermore, the creation of the videos went through several drafts until the coach deemed it was a suitable delivery of instructions. In contrast, the neutral video presented the basic rules of soccer with similar diagrammatic representations implemented to avert participants from making a link between the intention of the video and the subsequent task.

Three independent raters watched each trial and separately rated whether the best decision was congruent with at least one of the instructions (18/30 trials) or incongruent with all three instructions (12/30 trials). In the case that a certain trial was not agreed by all three reviewers if the best option was positively aligned with the coaching instructions or not, a fourth reviewer was asked to watch the trials and the majority ruled.

2.4. Apparatus

A mobile, head-mounted, binocular eye-tracking system (ETG 2.0 by SensoMotoric Instrument, Teltow, Berlin, Germany) with proprietary recording software (Version 2.6, iViewETG) was used to record visual search strategy with a sampling frequency of 24 Hz. The recording of the eye-tracking data was controlled through a wired connection by a connected laptop (Lenovo, Beijing, China). A positional cursor was used to identify visual point of gaze with a manual three-point calibration by the tester.

2.5. Procedure

Participants completed two 30-minute sessions, with a four week separation to negate any learning effects, and allow for a wash-out period (Woods, Williams, & Tavel, 1989). Upon arrival, participants completed a generic sports participation history questionnaire that asked for participants’ years of experience playing soccer, their current playing position, age and preferred foot. Prior to testing, eye-tracking glasses (ETG 2.0 by SensoMotoric Instrument, Teltow, Berlin, Germany) were calibrated at 1.5 m away from the projector screen. To ensure adequate calibration, this process was repeated after the five practice scenarios, and between blocks of 10 videos. After the calibration of the eye-tracking glasses, participants watched either a precueing video (1:33 min) or a neutral video (1:13 min) projected onto a 2.65 m high x 4.35 m wide screen positioned 4.4 m from the participant using a projector (Sony, XGA VPL-CX70, Japan) (see Figure 2).

Following the completion of the video, participants completed five practice trials of various scenarios. Participants then completed the 30 aforementioned offensive game-play trials in a randomized order. An inter-trial rest period of 10 seconds was administered between each clip. Participants were required to watch the soccer scenarios and execute a response action as quickly and as accurately as possible following the occlusion of each video. Participants responded by either: i) passing the ball to another team mate on the screen, ii) shooting the ball towards the goal, or iii) dribbling the ball as if they are moving around a defender. Participants performed one of the three movements with a soccer ball placed 1 m in front of them as depicted in Figure 2. Additionally, participants were asked to immediately verbalize their intended decision and response after each scenario.

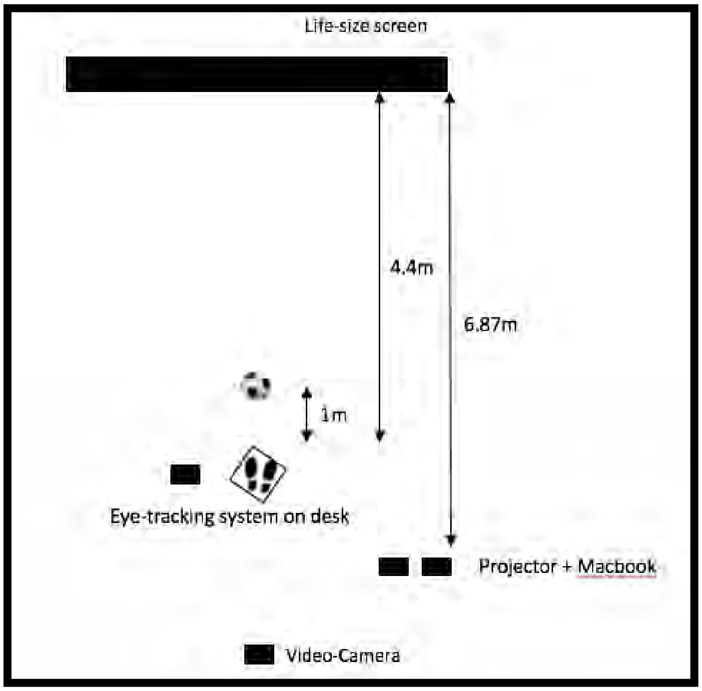

Figure 2: A diagrammatic representation of the laboratory testing procedure adapted from Vaeyens, Lenoir, Williams, Mazyn, et al. (2007).

2.6. Dependent variables

2.6.1. Decision-making

Response accuracy: Three nationally accredited coaches subjectively determined a four-point scale based on the most ideal decision that would lead to a goal scoring opportunity. In accordance with Vaeyens, Lenoir, Williams, Mazyn, et al. (2007), i) 3 points – the most goal oriented action that will directly lead to a goal scoring opportunity; ii) 2 points – not the most goal oriented action, however it is likely that it will create a goal scoring opportunity; iii) 1 point – allows for the maintenance of possession but doesn't create a goal scoring opportunity, and; iv) 0 points – an action that is likely to result in the loss of possession. Response accuracy was measured as a percentage of the total score available for each situation, with a total score out of 60 points.

Response time: Response time was measured as the time taken following the occlusion at the critical decision moment to the initiation of response, recorded when the participant raised their heel off the floor from either foot with intention to kick the ball (ms). A Garmin VIRB (Schaffhausen, Switzerland) video recording device was used to record participant's movement (120 fps). Analysis was conducted using a frame-by-frame approach with Kinovea software (version 0.8.15, Kinovea open source project, www.kinovea.org).

Frequency of response: Frequency of responses was measured as the amount of times a participant selected a certain response in each condition. Response choices were: pass right, pass left, pass centre/centre right/centre left, shoot and dribble.

2.6.2. Visual search data

Fixation location % (per scenario) for one of nine areas listed was analysed manually: 1. yellow offensive player [YP]; 2. player in possession of the ball [PB] ; 3. ball [B]; 4. unmarked attacker [A]; 5. attacker closely marked by a defender [A/D]; 6. defender [D]; 7. goalkeeper [K]; 8. free space [FS]; and 9. unspecified areas that did not match the aforementioned areas [U]. Analysis was conducted using a frame-by-frame approach with Kinovea analysis software. Data was collected from the initiation of the video until the occlusion of the video.

2.7. Statistical analysis

For statistical analysis, SPSS 24.0 (IBM, New York, United States) was used. Data are presented as mean ± SD. Prior to analysis, data were tested for normality by visual analysis of box plots. A Repeated Measures Multivariate Analysis of Variance (RM-MANOVA) with two within-subject factors [condition (neutral x precue) and congruency (congruent x incongruent)] was used to analyse the differences in performance for each scenario (3vs.1, 3vs.2, 4vs.3 and 5vs.3). The 2vs.1 scenarios were not considered in the analysis as no scenarios were deemed incongruent with instructions. In all repeated measures analyses, Bonferroni corrections were applied for multiple comparisons, and partial eta squared effect sizes (ES) were used to analyse the magnitude of effects. Effect sizes were interpreted as follows: 0.02 = small; 0.13 = moderate; and >0.26 = large (Bakeman, 2005; Cohen, 1988). Furthermore, a Repeated Measures Analysis of Variance (RM-ANOVA) was used to analyse differences in the frequency of different responses given by the participants (pass left, pass right, pass centre, shoot, dribble). The criterion alpha level for significance was set at $p \leq 0.05$.

3. Results

3.1. Preparatory analysis

The reliability of the visual search behaviour analyses was assessed using intra-class correlation coefficient (ICC), with a wash out period of three months. The reliability was described as "excellent" for ICC values in the range of 0.8-1.0, "good" for 0.6-0.8, and "poor" for <0.6 (Shrout & Fleiss, 1979). Upon analysis, an excellent degree of reliability was observed in the visual search behaviour measurements. The average measure of ICC was 0.993 with a 95% confidence interval from 0.990 to 0.995 ($F(129,129) = 145.695$, $p < 0.001$). For univariate analyses, see Table 1 for decision-making variables and Table 2 for fixation location variables.

Table 1: Results of three types of responses under different conditions.

		Neutral		**Precue**		**Condition**		**Congruency**		**Interaction**	
		Congruent	**Incongruent**	**Congruent**	**Incongruent**						
	Scenario	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**F-value**	**ES**	**F-value**	**ES**	**F-value**	**ES**
Response Accuracy	3 vs. 1	2.95 (0.10)	2.62 (0.54)	2.67 (0.60)	2.24 (0.76)	4.622	0.262	6.241*	0.324	0.157	0.012
	3 vs. 2	2.55 (0.52)	2.71 (0.52)	2.71 (0.29)	2.19 (0.89)	4.452	0.255	0.663	0.049	5.315*	0.290
	4 vs. 3	1.63 (0.87)	2.43 (0.94)	1.68 (0.56)	2.43 (0.94)	0.047	0.004	5.084*	0.281	0.047	0.004
	5 vs. 3	2.43 (1.02)	2.67 (0.30)	2.57 (0.51)	2.31 (0.60)	0.668	0.049	0.003	<0.001	1.534	0.106
Response Time	3 vs. 1	569.924 (135.198)	569.773 (181.970)	540.188 (128.192)	569.242 (129.922)	0.174	0.017	0.418	0.040	0.810	0.075
	3 vs. 2	846.848 (230.951)	635.909 (258.894)	657.697 (230.848)	653.182 (183.067)	4.873	0.328	7.658*	0.434	6.256*	0.385
	4 vs. 3	686.295 (217.172)	754.909 (328.683)	647.114 (200.847)	675.909 (163.352)	1.150	0.103	1.403	0.123	0.278	0.027
	5 vs. 3	615.273 (157.279)	614.939 (160.947)	572.818 (238.208)	564.018 (161.819)	1.086	0.098	0.010	0.001	0.010	0.001
Frequency of Response	Pass Right	10.67 (1.291)		8.20 (3.278)		8.421*	0.376				
	Pass Left	4.67 (1.633)		2.93 (1.668)		7.608*	0.352				
	Pass Centre	2.47 (2.326)		2.93 (2.658)		0.560	0.038				
	Shoot	7.80 (1.612)		9.07 (1.981)		13.513**	0.491				
	Dribble	4.0 (2.699)		6.40 (5.422)		2.925	0.173				

Note: * = *p* < 0.05, ** = *p* < 0.01, ES = partial eta squared effect sizes. Effect sizes were interpreted as <0.02 as small; 0.13 as moderate; and >0.26 as large (Cohen, 1988).

Table 2: Results of fixation locations between different conditions

		Neutral		**Precue**							
		Congruent	**Incongruent**	**Congruent**	**Incongruent**	**Condition**		**Congruency**		**Interaction**	
Fixation Location	**Scenario**	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**F**	**ES**	**F**	**ES**	**F**	**ES**
YP	3 vs. 1	0.114 (0.047)	0.253 (0.113)	0.104 (0.059)	0.239 (0.111)	2.588	0.301	20.445**	0.773	0.025	0.004
	3 vs. 2	0.221 (0.085)	0.274 (0.090)	0.219 (0.062)	0.186 (0.073)	2.199	0.268	0.310	0.049	11.881*	0.664
	4 vs. 3	0.161 (0.066)	0.171 (0.059)	0.089 (0.039)	0.104 (0.078)	6.492*	0.520	1.717	0.223	0.025	0.004
	5 vs. 3	0.214 (0.059)	0.173 (0.085)	0.227 (0.064)	0.166 (0.067)	0.016	0.003	7.943*	0.570	0.750	0.111
PB	3 vs. 1	0.423 (0.064)	0.234 (0.063)	0.440 (0.116)	0.199 (0.053)	0.113	0.019	53.557**	0.899	1.021	0.145
	3 vs. 2	0.424 (0.118)	0.381 (0.052)	0.446 (0.135)	0.393 (0.143)	0.083	0.014	1.737	0.224	0.047	0.008
	4 vs. 3	0.336 (0.103)	0.260 (0.085)	0.366 (0.111)	0.296 (0.113)	6.626*	0.525	4.125	0.407	0.011	0.002
	5 vs. 3	0.254 (0.112)	0.301 (0.077)	0.304 (0.098)	0.286 (0.058)	0.129	0.021	1.742	0.225	1.338	0.182
B	3 vs. 1	0.199 (0.102)	0.116 (0.089)	0.147 (0.114)	0.179 (0.104)	0.106	0.017	2.046	0.254	24.304**	0.802
	3 vs. 2	0.030 (0.058)	0.033 (0.037)	0.016 (0.024)	0.049 (0.060)	0.007	0.001	2.765	0.315	1.099	0.155
	4 vs. 3	0.079 (0.076)	0.164 (0.108)	0.076 (0.061)	0.051 (0.086)	8.107*	0.575	2.168	0.265	3.309	0.355
	5 vs. 3	0.036 (0.029)	0.033 (0.048)	0.031 (0.043)	0.011 (0.011)	3.096	0.340	2.400	0.286	0.377	0.059
A	3 vs. 1	0.061 (0.032)	0.060 (0.055)	0.066 (0.033)	0.089 (0.074)	2.394	0.285	0.385	0.060	1.633	0.214
	3 vs. 2	0.011 (0.016)	0.019 (0.011)	0.019 (0.020)	0.020 (0.021)	0.462	0.071	1.350	0.184	0.632	0.095
	4 vs. 3	0.003 (0.008)	0.010 (0.019)	0.001 (0.004)	0.003 (0.008)	1.241	0.171	0.939	0.135	0.495	0.076
	5 vs. 3	0.036 (0.037)	0.101 (0.064)	0.051 (0.058)	0.106 (0.030)	0.651	0.098	5.352	0.471	0.149	0.024
A/D	3 vs. 1	<0.001 (<0.001)	<0.001 (<0.001)	0.001 (0.004)	<0.001 (<0.001)	1.000	0.143	1.000	0.143	1.000	0.143
	3 vs. 2	0.053 (0.059)	0.041 (0.038)	0.120 (0.256)	0.049 (0.045)	0.627	0.095	0.513	0.079	0.607	0.092
	4 vs. 3	0.174 (0.117)	0.097 (0.080)	0.140 (0.072)	0.171 (0.067)	0.532	0.082	0.828	0.121	7.402	0.552
	5 vs. 3	0.184 (0.087)	0.139 (0.062)	0.116 (0.045)	0.173 (0.029)	0.680	0.102	0.345	0.054	7.722	0.563
D	3 vs. 1	0.051 (0.033)	0.116 (0.066)	0.124 (0.101)	0.121 (0.059)	4.287	0.417	1.850	0.236	3.421	0.363
	3 vs. 2	0.109 (0.100)	0.077 (0.064)	0.106 (0.093)	0.157 (0.102)	2.377	0.284	0.420	0.065	6.169	0.507
	4 vs. 3	0.051 (0.039)	0.111 (0.085)	0.132 (0.056)	0.216 (0.194)	3.939	0.396	5.424	0.475	0.087	0.014
	5 vs. 3	0.053 (0.042)	0.049 (0.027)	0.057 (0.035)	0.061 (0.025)	0.429	0.067	<0.001	<0.001	0.229	0.037
K	3 vs. 1	0.017 (0.029)	0.051 (0.076)	0.017 (0.022)	0.021 (0.021)	0.922	0.133	2.324	0.279	4.021	0.401
	3 vs. 2	0.006 (0.005)	0.017 (0.030)	0.031 (0.042)	0.017 (0.037)	1.617	0.212	0.028	0.005	4.359	0.421
	4 vs. 3	0.007 (0.015)	0.013 (0.026)	0.024 (0.022)	0.024 (0.046)	1.030	0.147	0.123	0.020	0.078	0.013
	5 vs. 3	0.031 (0.079)	0.014 (0.025)	0.034 (0.051)	0.016 (0.011)	0.037	0.006	0.707	0.105	0.002	<0.001
FS	3 vs. 1	0.027 (0.016)	0.019 (0.025)	0.060 (0.049)	0.026 (0.025)	1.461	0.196	4.397	0.423	1.717	0.223
	3 vs. 2	0.016 (0.010)	0.013 (0.014)	0.017 (0.024)	0.013 (0.013)	0.008	0.001	0.728	0.108	0.011	0.002
	4 vs. 3	0.030 (0.034)	0.034 (0.033)	0.034 (0.032)	0.031 (0.043)	0.003	<0.001	0.005	0.001	0.257	0.041
	5 vs. 3	0.006 (0.008)	0.030 (0.020)	0.014 (0.014)	0.021 (0.013)	<0.001	<0.001	60.5**	0.910	1.946	0.245
U	3 vs. 1	0.006 (0.008)	0.021 (0.042)	<0.001 (<0.001)	0.001 (0.004)	2.730	0.313	1.108	0.156	0.781	0.115
	3 vs. 2	0.006 (0.015)	0.001 (0.004)	<0.001 (<0.001)	0.007 (0.019)	<0.001	<0.001	0.083	0.014	1.670	0.218
	4 vs. 3	0.019 (0.041)	<0.001 (<0.001)	0.006 (0.011)	<0.001 (<0.001)	0.563	0.086	2.643	0.306	0.563	0.086
	5 vs. 3	0.020 (0.017)	0.010 (0.013)	0.019 (0.024)	0.004 (0.005)	0.434	0.067	2.959	0.330	0.102	0.017

Note: * = $p < 0.05$, ** = $p < 0.01$, ES = partial eta squared effect sizes. Effect sizes were interpreted as 0.02 as small; 0.13 as moderate; and 0.26 as large (Cohen, 1988). a) Yellow offensive player [YP]; b) player in possession of the ball [PB]; c) ball [B]; d) unmarked attacker [A]; e) attacker closely marked by a defender [A/D]; f) defender [D]; g) goalkeeper [K]; h) free space [FS]; and i) unspecified areas that did not match the aforementioned areas [U].

3.2. Response accuracy

The RM-MANOVA did not reveal a significant condition x congruency interaction effect in response accuracy. However, a trend towards a main effect of test condition (F = 3.023, *p* = 0.07, ES = 0.547) and a significant large main effect of congruency (F = 3.705 *p* = 0.042, ES = 0.597) was apparent. Further univariate analysis revealed a trend towards a main effect of condition and congruency in the 3vs.1 and the 3vs.2 scenarios. Overall, the neutral condition (85.85 ± 4.41 %) yielded a higher response accuracy compared to the precue condition (80.81 ± 8.40 %; Figure 3C). Furthermore, response accuracy was higher in precue congruent scenarios and lower in precue incongruent scenarios compared to their neutral scenarios (Figure 3A, B).

3.3. Response time

No significant condition x congruency interaction effects on response time were observed. However, further univariate analysis revealed a condition x congruency interaction effect, and a large main effect of condition and congruency in the 3vs.2 scenarios. Yet, the precue condition was faster (590.75 ± 203.47 ms) compared to the neutral condition (630.47 ± 241.55 ms; Figure 3F). Furthermore, the precue condition consistently yielded faster response times for both the congruent and incongruent scenarios compared to the neutral condition (Figure 3D, E). Although, the incongruent 3vs.2 scenarios were slower than the neutral scenarios.

3.4. Fixation location

3.4.1. Condition x congruency

Multiple RM-MANOVA's revealed a trend towards a significant condition x congruency interaction effect on YP and A/D (F = 6.557, *p* = 0.077, ES = 0.897; F = 10.052, *p* = 0.044, ES = 0.931) respectively. Univariate analysis revealed a condition x congruency interaction effect of B and K in 3vs.1 (F = 24.304, *p* = 0.003, ES = 0.802; F = 4.021, *p* = 0.092, ES = 0.401); of YP, D and K in 3vs.2 (F = 11.881, *p* = 0.014, ES = 0.664; F = 6.169, *p* = 0.048, ES = 0.507; F = 4.359, *p* = 0.082, ES = 0.421); of A/D in 4vs.3 (F = 7.402, *p* = 0.035, ES = 0.552) and of A/D in 5vs.3 scenarios (F = 7.722, *p* = 0.032, ES = 0.563) respectively.

3.4.2. Condition

Multiple RM-MANOVA's revealed a significant and large main effect of condition in PB (F = 63.401, *p* = 0.003, ES = 0.988). Further univariate analysis revealed a trend in the large main effect of D in 3vs.1 (F = 4.287, *p* = 0.084, ES = 0.417); and significantly large main effect of YP, PB, B and a trend in D in 4vs.3 scenarios (F = 6.492, *p* = 0.044, ES = 0.52; F = 6.626, *p* = 0.042, ES = 0.525; F = 8.107, *p* = 0.029, ES = 0.575; F = 3.939, *p* = 0.094, ES = 0.396) respectively (Figure 4C).

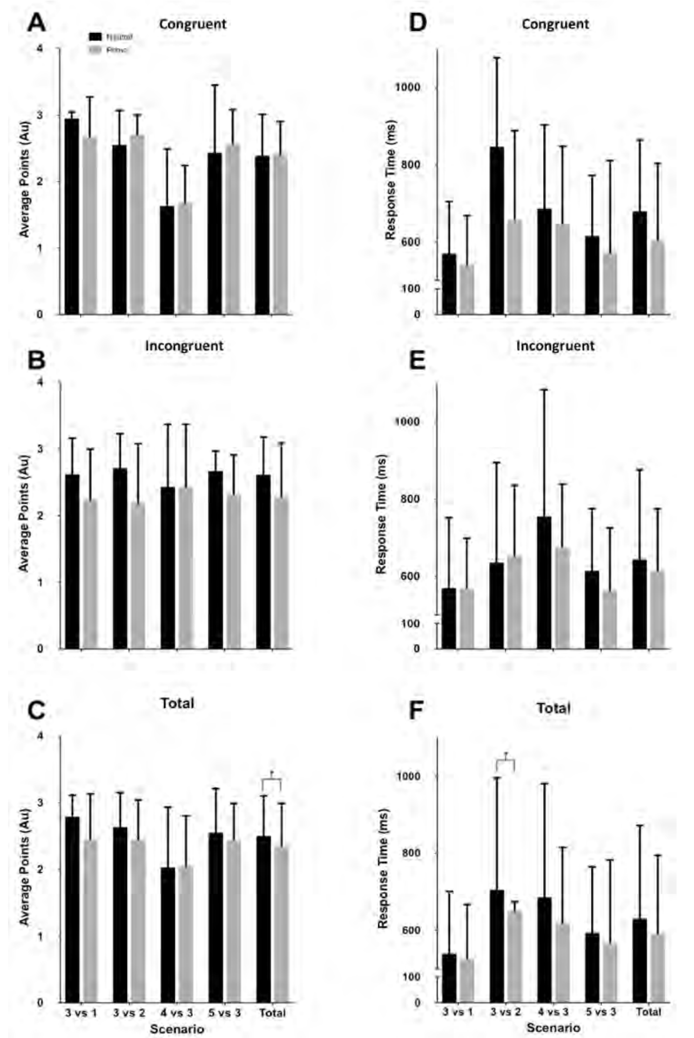

Figure 3: Effects of precues on response accuracy (A-C) and response time (D-F).

3.4.3. Congruency

Multiple RM-MANOVA's revealed a significant and large main effect of congruency in YP (F = 9.257, *p* = 0.049, ES = 0.925), PB (F = 12.136, *p* = 0.034, ES = 0.942) and FS (F = 143.022, *p* = 0.001, ES = 0.995). Further univariate analysis revealed large main effects of YP, PB and a trend in FS in 3vs.1 (F = 20.445, *p* = 0.004, ES = 0.773; F = 53.557, *p* < 0.001, ES = 0.899; F = 4.397, *p* = 0.081, ES = 0.423); trends in the large main effect of PB and D in 4vs.3 (F = 4.125, *p* = 0.089, ES = 0.407; F = 5.424, *p* = 0.059, ES = 0.475); and of YP, A, and FS (significant) in 5 vs 3. scenarios (F = 7.943, *p* = 0.03, ES = 0.57; F = 5.352, *p* = 0.06, ES = 0.471; F = 60.5, *p* < 0.001, ES = 0.910) (Figure 4A, B).

Overall, the neutral condition yielded a higher percentage of time spent fixating on the yellow player compared to the precue condition (Figure 4C), and in both congruent and incongruent scenarios (Figure 4A, B). Yet, the precue condition yielded a higher percentage of time spent fixating on defenders compared to the neutral condition, and in both congruent and incongruent scenarios.

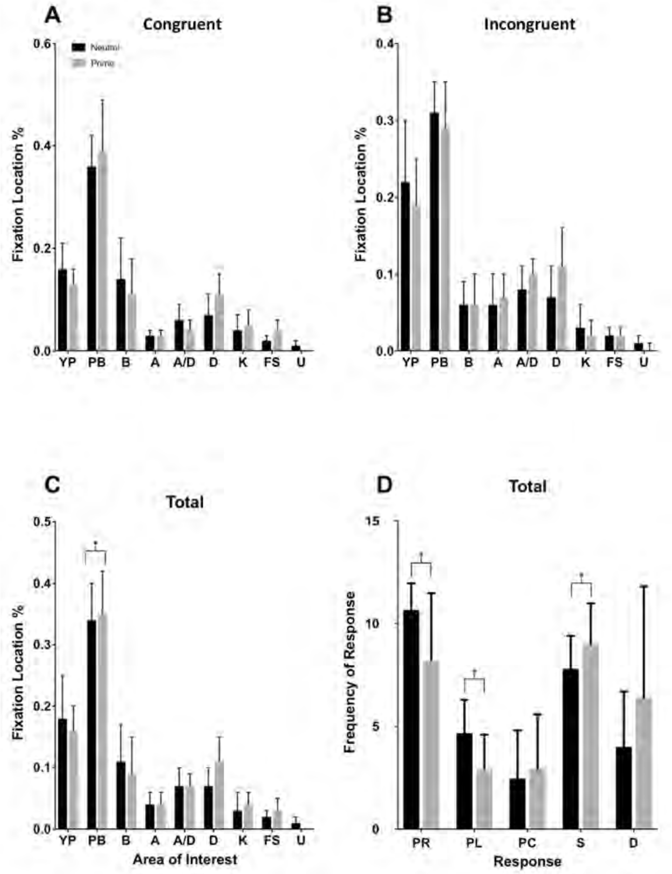

Figure 4: Effects of precues on fixation location (A-C) and frequency of response (D). Graph D abbreviations are as follows: PR (pass right), PL (pass left), PC (Pass centre), S (shoot) and D (dribble).

3.5. Frequency of responses

The RM-ANOVA revealed a significant and large main effect of test condition (F = 4.494, *p* = 0.021, ES = 0.692). Further univariate analysis revealed a significantly large main effect in the 'pass right', 'pass left' and 'shoot' (F = 8.421, *p* = 0.012, ES = 0.376; F = 7.608, *p* = 0.015, ES = 0.352; F = 13.513, *p* = 0.002, ES = 0.491) respectively. Overall, 'pass right' and 'pass left' were lower, and 'pass centre', 'shoot' and 'dribble' were higher in the precue condition compared to the neutral condition.

4. Discussion

Coaches often use instructions before a game to encourage or discourage tactical responses from their players during a game. These instructions often contain information of how the opposition is likely to play, or how athletes should act in specific circumstances (Farrow, Baker, & MacMahon, 2013). Accordingly, the aim of this study was to determine if precueing using tactical instructions influences soccer players' decision-making skill in a sport-specific task through the investigation of visual search behaviour, response accuracy and response time. The primary finding of the current investigation was that tactical instructions provided using simulated coaching instructions impaired the accuracy of soccer-specific decision-making skill, but slightly enhanced participants' response time. Additionally, fixation location data demonstrated that athletes did not differ regarding their visual search patterns between conditions, highlighting that similar information was extracted from the performance environment with or without instructions.

Overall, response accuracy was significantly lower in the precue condition compared to the neutral condition. This is in line with other studies reporting that an adherence to explicit instructions was also detrimental to the decision-making accuracy of low-experienced level players in Australian football (Buszard et al., 2013) and handball (Memmert & Furley, 2007). Conversely, response times were revealed to be consistently faster across all scenarios in the precue condition compared to the neutral condition. This finding contradicted the main hypothesis that the precue condition would have both inferior response accuracy and response time compared to the neutral condition. It was expected that athletes would have slower response times associated with incompatible precues due to the inhibition of return effect demonstrated in previous precueing studies (Beavan et al., 2019; Posner, Rafal, Choate, & Vaughan, 1985; Rosenbaum & Kornblum, 1982). This inhibition process refers to when a movement towards the likely target's location must be cancelled, and attention must then be redirected to the actual location of the target allowing for a new movement program towards the correct location of the target to be created (Elliott, 2004).

One explanation for the observed faster response times and worse accuracy scores in the precue condition may be linked with the decision-making heuristics of taking the options that only aligned with the prior instructional precues. For example, when precues were congruent with the scenario, response accuracies were similarly accurate to when no precue was given in the same scenarios as the neutral condition, but they had faster initiation times demonstrating the advantage of beneficial precues (Posner et al., 1980). However, when confronted with situations that were incongruent with the precues, a large decrease in response accuracy was observed, yet the athletes still responded faster than the neutral condition. This implies that athletes did not make the most correct decision due to the adherence of the precues, and their response times indicate that their motor behaviour was primed to act in accordance with this heuristic. Decision-making heuristics have previously been observed in a sporting domain. Buszard et al. (2013) discussed the 'take the first option (TTF)' heuristic. In about 60% of scenarios, TTF may benefit the athletes (i.e., a congruent heuristic), yet in the other 40% scenarios the first option is not the best option (i.e., an incongruent heuristic) but nevertheless a player's attention is drawn to incorrect environmental cues leading to possible wrong decisions being generated. In support, the frequency of 'pass right' and 'pass left' were lower, and 'pass centre', 'shoot' and 'dribble' were higher in the precue condition compared to the neutral condition; demonstrating adherence to instructions.

Discrepancies in decision-making performance may further be attributed to changes in attention, as previous studies demonstrated instructions can guide an athlete's attentional focus (Williams, Davids, & Williams, 1999) and change breadth-of-attention (Memmert & Furley, 2007). Memmert and Furley

(2007) demonstrated that when athletes in handball were given two common instructions related to observing a specific defender, 83% of the instructional group failed to notice the free defender compared to 17% of the no-instructions group. Although inattentional blindness ('blindness' as a result of 'not paying attention' to a cue) was not the primary focus of this study, it is plausible the instructions given may have directed the participants' attention to different cues in the environment. Similar to Buszard et al., (2013), the main visual search patterns remained unchanged between instructional conditions, and the results did not provide strong evidence in support the hypothesis that athletes had different visual fixation patterns in between conditions. However, the lack of differences reported in participants visual search behaviour is an important finding in itself. The fact that visual search behaviour remaining largely unchanged, but other response measures were affected by the precues demonstrates that the precues indeed have a constraining effect. Athletes appear to still perceive the same information in the environment, but they do not couple it with appropriate action as effectively. Indeed, such results provides evidence that is in favour of hands-off pedagogical strategies such as the constraints-led approach (Davids, Button, Araújo, Renshaw, & Hristovski, 2006). Coaches are recommended to manipulate the constrains of training drills in order to elicit a technical and tactical behaviour without having to explicitly instruct the athletes to do so. For example, Otte et al. (2020) reports a case study on how Nonlinear Pedagogy and Constraints-Led approaches can be used for training professional football goalkeepers.

Certain limitations must be considered when interpreting the observed findings. First, the eye-tracking glasses were connected by a cable to a laptop stationed to the side of the participant, possibly restricting the participants' movements. Second, the present findings are limited by the small sample size as the gaze behaviour was recorded in only seven participants. Additionally, the use of a video-based decision-making task - although popular due to the advantage of internal validity, reliability and ethical considerations (Mann, Williams, Ward, & Janelle, 2007) - has questionable ecological validity as key environmental conditions such as crowd noise, physical exertion and performance pressure could not be included. Finally, the methodology of this study was based on the concept that athletes are provided with coaching instructions prior to the commencement of a match. Yet, it is unknown how long these effects last, or whether certain types of instructions induce a larger change in sporting-performance. Therefore, future research should implement and compare different instructional approaches, and modify the content and method of delivery of the pre-cues.

To conclude, experiments that deliberately manipulate how information and movement are coupled in a response time task present an interesting avenue for researchers interested in adopting a priming-based approach to explain perceptual-motor control in sport. The present study examined the influence of instructional precues on decision-making in a video-based soccer-specific decision-making task, revealing that coaching instructions are not always beneficial to performance. The findings of this study suggest certain instructional language may negatively influence an athlete's decision-making skill in scenarios where the correct response does not correspond with a specific instructions. Coaches should therefore consider integrating a more self-discovery approach in training, blinding athletes to the true incentive of the training drill that allows for creative behaviour in the athletes. This can be completed by coaches being aware of explicitly 'over-instructing' and 'over-coaching' athletes. From a practical perspective, the coach should reduce the use of explicit tactical instructions, and provide better guidance during training. Coaches should aim to design environments that allow for a certain behaviour to emerge without explicitly instructing their athletes to act in such way.

Conflict of Interest

The authors declare no conflict of interests.

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Propensity for conscious control of movement is unrelated to asymptomatic hypermobility or injury-risk scores

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Beighton Hypermobility Scale

A B S T R A C T

The Movement Specific Reinvestment Scale (MSRS) measures the propensity for conscious monitoring and control of movement, which can inhibit automated movement processes, potentially causing movement disruption or injury. High injury risk individuals are more likely to make movement errors during jump-landing tasks, and hypermobile individuals present with poor movement control. The link between MSRS and these characteristics remains largely unexplored. Consequently, we examined propensity for movement specific reinvestment in high injury risk and asymptomatic hypermobile participants. Sixty volunteers (35 males, 25 females) were tested using the MSRS, Landing Error Scoring System (LESS), and Beighton hypermobility scale. Spearman rank correlation coefficients were computed between MSRS, LESS, and Beighton scores. Furthermore, MSRS scores were compared between low (LESS $<$ 5 errors) and high (LESS $\geq$ 5 errors) injury risk, as well as non-hypermobile and hypermobile participants. MSRS scores were not significantly related to LESS ($\rho = 0.06$, $p = 0.625$) or Beighton ($\rho = 0.09$, $p = 0.481$) scores. MSRS scores of low and high injury risk (37.8 ± 7.8 vs 38.0 ± 8.6, $p = 0.933$), and non-hypermobile and hypermobile (37.5 ± 8.9 vs 39.0 ± 7.0, $p = 0.524$) participants were comparable. Based on our results, there is no evidence that movement specific reinvestment contributes to injury risk assessed by LESS, which might be due to the phylogenetic nature of the LESS jump-landing task and/or the low psychological pressure environment of laboratory testing. The propensity for movement specific reinvestment did not vary in asymptomatic hypermobile individuals compared to non-hypermobile individuals; however, examination of the MSRS in symptomatic hypermobile individuals and individuals with well-defined syndromes is needed to fully elucidate whether or not conscious monitoring and control of movement plays a role in injury risk or movement control across the hypermobility spectrum.

1. Introduction

It is well known that human movements are influenced by various psychological factors, such as fear of movement-related pain (Meulders, Vansteenwegen, & Vlaeyen, 2011), motivation (Kadosh & Staunton, 2019), or reinvestment (Masters, 1992; Masters & Maxwell, 2008). Reinvestment is defined as 'manipulation of conscious, explicit, rule based knowledge, by working memory, to control the mechanics of one's movements during motor output' (Masters & Maxwell, 2004, p. 208). The Movement Specific Reinvestment Scale (MSRS) is a valid and reliable measure of the propensity for conscious involvement in movement (Masters, Eves, & Maxwell, 2005; Wong, Masters, Maxwell, & Abernethy, 2008). The MSRS consists of 10 statements about a person's tendency to consciously process their movements or to be self-conscious about their style of movement (Table 1). Scoring of the MSRS statements is based on a Likert-type scale ranging from strongly agree (1 point) to strongly disagree (6 points). The maximum MSRS score is 60 points, with higher scores indicating greater propensity to consciously monitor and control movements. The theory of reinvestment proposes that consciously controlling and monitoring one's own movements can constrain or inhibit more effective automatic control processes, which can potentially lead to movement disruption (Masters & Maxwell, 2008). High MSRS scores are associated with greater movement errors under psychological pressure in

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sport (Chell, Graydon, Crowley, & Child, 2003; Jackson, Ashford, & Norsworthy, 2006; Masters, Polman, & Hammond, 1993; Maxwell, Masters, & Poolton, 2006), slowed surgical performance by medical students under time pressure (Malhotra, Poolton, Wilson, Ngo, & Masters, 2012), higher fall incidence in older adults (Wong et al., 2008), more severe functional impairment after stroke (Orrell, Masters, & Eves, 2009), duration of Parkinson's disease (Masters, Pall, MacMahon, & Eves, 2007), and self-reported knee pain (Selfe et al., 2015).

The Landing Error Scoring System (LESS) is a reliable and valid injury risk screening tool that identifies movement patterns linked with non-contact injuries using a jump-landing task (Hanzlíková & Hébert-Losier, 2020). Clinicians evaluate frontal and sagittal plane videos from the LESS test and visually evaluate aberrant lower extremity and trunk kinematics from initial ground contact until maximal knee flexion. The LESS score consists of 17 items; movement items 1 to 15 are scored as 0 (error absent) or 1 (error present). The last two items (16 and 17) are subjective and assess the overall sagittal plane displacement and quality of landing. These two items are scored from 0 to 2 errors. The minimum (best) score is 0 and reflects the absence of movement errors, and the maximum (worst) score is 17 errors. Higher LESS scores indicate poorer jump-landing mechanics and greater risk of non-contact lower extremity injury. Padua et al. (2015) concluded that 5 errors was the optimal cut-off score for determining increased risk of non-contact Anterior Cruciate Ligament (ACL) injury incidence. The risk ratio for sustaining a non-contact ACL injury when LESS scores were 5 errors or greater (compared to lower than 5 errors) was 10.7 (Padua et al., 2015). A previous study concluded that elder fallers scored significantly higher on the MSRS compared to non-fallers (Wong et al., 2008). The authors argued that the high propensity to reinvest might contribute to cautious gait in those with fear of falling, which disrupts automaticity of walking and increases risk of falling and associated injury risk (Wong et al., 2008). Therefore, it is possible that athletes who consciously monitor their own movements may exhibit a greater number of landing errors during LESS assessment and be at greater risk of sport-related injuries.

Generalized hypermobility is an identified risk factor for injury (Dallinga, Benjaminse, & Lemmink, 2012; Donaldson, 2012; Pacey, Nicholson, Adams, Munn, & Munns, 2010), including the ACL injury (Goshima, Kitaoka, Nakase, & Tsuchiya, 2014; Sundemo et al., 2019). Generalized joint hypermobility is usually a congenital inherited disorder of connective tissue characterized by increased movement in multiple joints beyond normal physiological ranges expected in a given population (Castori et al., 2017; Malfait et al., 2017). Overall, the prevalence of generalized hypermobility reported to exist in the general population is between 10 to 20% (Remvig, Jensen, & Ward, 2007b). Generalized joint hypermobility can be categorized as individuals with asymptomatic joint hypermobility, individuals with well-defined syndrome associated with joint hypermobility, and individuals with symptomatic joint hypermobility (Castori et al., 2017). Besides a range of musculoskeletal symptoms (Hakim & Grahame, 2003), generalized hypermobility has been associated with a greater prevalence of panic disorder and anxiety (Garcia-Campayo, Asso, & Alda, 2011), attention-deficit and hyperactivity disorder (Baeza-Velasco, Sinibaldi, & Castori, 2018), fatigue (Krahe, Adams, & Nicholson, 2018), and pain hypersensitivity (Bettini, Moore, Wang, Hinds, & Finkel, 2018). Given that the propensity for movement specific reinvestment has also been linked to fear, anxiety, fatigue, and movement difficulties and disorders, there may be an association between hypermobility and conscious engagement in movement. Conscious engagement in movement may therefore be contributing to the altered movement patterns (Fatoye, Palmer, Van der Linden, Rowe, & Macmillan, 2011; Galli et al., 2011; Luder et al., 2015; Simonsen et al., 2012) and increased injury risk (Pacey et al., 2010) in hypermobile individuals.

The association between propensity for movement specific reinvestment, biomechanical control, and hypermobility has not been studied to date. The propensity for movement specific reinvestment may be an important injury risk factor to consider that may assist injury prevention efforts via the development and implementation of more targeted, multi-modal interventions for these individuals. Participants with symptomatic generalized joint hypermobility or well-defined syndromes associated with hypermobility often present with chronic pain and fatigue to various extents, which may influence the results. Several physically active individuals present with asymptomatic generalized joint hypermobility (Luder et al., 2015) and are clinically perceived at a higher risk of injury given their hypermobile status, although limited research has focused on this population specifically. Therefore, the aim of this paper was to explore the relationship between MSRS, LESS, and Beighton scores in young active asymptomatic individuals, as well as to compare MSRS scores between participants at low and high injury risk, as well as between non-hypermobile and asymptomatic generalized hypermobile participants. We hypothesized that participants at high injury risk and those presenting with asymptomatic generalized hypermobility would exhibit greater MSRS scores than low injury risk and non-hypermobile participants, respectively.

Table 1: The Movement Specific Reinvestment Scale. Adapted from Masters et al. (2005).

Conscious Motor Processing items
I remember the times when my movements have failed me.
I reflect about my movement a lot.
I try to think about my movements when I carry them out.
I am aware of the way my body works when I am carrying out a movement.
I try to figure out why my actions failed.
Movement Self-Consciousness items
If I see my reflection in a shop window, I will examine my movements.
I am self-conscious about the way I look when I am moving.
I sometimes have the feeling that I am watching myself move.
I am concerned about my style of moving.
I am concerned about what people think about me when I am moving.

2. Methods

2.1. Participants

Given that no published data exist regarding the association between MSRS, LESS, and Beighton scores, we calculated sample size requirements based on the ability to detect a correlation of moderate magnitude (i.e., 0.50) (Mukaka, 2012). Based on sample size calculations using a customizable statistical spreadsheet (Hopkins, 2006) from standard two-tailed hypothesis equations using an 90% power (β = 0.10) and 5% significance level (α = 0.05), we needed at least 38 participants to detect a moderate correlation between measures. Given that 60 individuals agreed to participate, our study sample size is powered to detect a correlation of 0.40 in magnitude.

To be included, participants needed to be involved in sport activity; and be free from injury, pain, or any other issue that would limit physical activity at the time of study participation. Previous injuries were not an exclusion criterion. This study aimed to assess only non-hypermobile and asymptomatic hypermobile participants according to the framework for the classification of joint hypermobility proposed by Castori et al. (2017). Therefore, participants with chronic pain or known diagnosis of medical syndromes associated with joint hypermobility (e.g., Ehlers Danlos and Marfan syndrome) were excluded. Sixty young adults (35 males, 25 females) fulfilled the inclusion criteria and participated in this study. Age, height, and mass (mean ± standard deviation) for males were 23.2 ± 4.7 years, 181.2 ± 6.6 cm, and 83.9 ± 3.2 kg; and 22.2 ± 5.6 years, 169.3 ± 5.8 cm, and 66.2 ± 2.6 kg for females. Participants were involved in organized sport activity 3 times per week (median), on average for 6.4 ± 4.4 hours a week. The study protocol was approved by our institution's Health Research Ethics Committee [HREC(Health)#2018-27] and adhered to the Declaration of Helsinki. All participants signed a written informed consent document that explained the potential risks associated with testing before participating. Note that participants were not screened for generalized joint hypermobility prior to participation.

2.2. Procedure

All tests were completed in a single session. After self-administered MSRS completion, half of the participants completed the LESS protocol followed by the Beighton diagnostic test for hypermobility, whereas the other half completed the tests in the reverse order. The MSRS has adequate internal reliability (coefficient alpha = 0.80), teste-retest reliability (Pearson product moment correlation coefficient = 0.74), and validity (Masters et al., 2005; Masters et al., 1993). The LESS has been validated against 3D motion capture and has good-to-excellent intrarater [intraclass correlation coefficient (ICC), 0.82-0.99], interrater (ICC, 0.83-0.92), and intersession (ICC, 0.81) reliability reported in the scientific literature (Hanzlíková & Hébert-Losier, 2020). The Beighton score is a major criterion used in diagnosing joint hypermobility syndrome, and is a valid and reliable (kappa = 0.75 to 0.78) diagnostic tool for joint hypermobility (Remvig, Jensen, & Ward, 2007a). In this study, sex and age-specific cut-off scores based on Singh et al. (2017) were used to categorize hypermobility. Specifically, the cut-off score for hypermobility of ≥ 5 points was used for females, and ≥ 4 for males in our sample.

The LESS testing procedure used here was identical to the procedure described elsewhere (Padua et al., 2009). Participants jumped horizontally from a 30-cm high box to a line placed at 50% of their body height, and immediately jumped upward for maximal vertical height. Participants were instructed to jump off the box with both feet, land in front of the designated line, and jump as high as possible upward upon landing. We provided no feedback on landing technique unless participants were performing the task incorrectly. Participants were given as many practice trials as needed to become comfortable with the task (typically one). Each participant performed three trials of the double-leg jump-landing task in their own footwear. To mitigate effects of fatigue, participants were allowed to rest until they felt ready to perform the second and third trial of the task. Two tripod-mounted digital cameras (Sony RX10 II, Sony Corporation, Tokyo, Japan) with an actual focal length of 8.8 to 73.3 mm (35-mm equivalent focal length of 24-200 mm) captured performance of the task at 60 Hz. The cameras were placed 3.5 m in front of and to the right side of the landing area with a lens-to-floor distance of 1.3 m to capture frontal and sagittal plane motion. One investigator (IH) with experience of over 400 LESS evaluations replayed the videos using the open-source Kinovea video analysis software (version 0.8.15, www.kinovea.org). The investigator scored the first landing of the jump-landing task of all three trials (i.e., when landing from the box) using the 17-item LESS scoring criteria (Padua et al., 2009). The investigator was blinded to the MSRS and Beighton hypermobility scores.

An experienced physiotherapist (IH) recorded the Beighton scores, consisting of five components: (1) passive dorsiflexion and hyperextension of the fifth metacarpal joints (little fingers) beyond 90°, (2) passive apposition of the thumbs to the flexor aspects of the forearms, (3) passive hyperextension of the elbows beyond 10°, (4) passive hyperextension of the knees beyond 10°, and (5) active forward flexion of the trunk with the knees fully extended so that the palms of the hands rest flat on the floor (Beighton, Solomon, & Soskolne, 1973), following standard protocols and using a hand-held goniometer (Smits-Engelsman, Klerks, & Kirby, 2011). Note here that the first four elements can be given a maximum score of 2 points because these are performed bilaterally (i.e., 1 point for each hypermobile joint), whereas the last element has a maximum score of 1 point. Hence, a total score of 9 points is possible.

2.3. Statistical approach

Mean ± standard deviation, median (interquartile range), and range (minimum to maximum) values were calculated to describe variables based on variable type. Note that the mean LESS score from the three trials completed by each participant was used for statistical analysis. Statistical significance level was set at $\alpha \leq 0.05$ for all analyses. The statistics were computed using Microsoft® Excel® for Office 365 MSO and RStudio® Version 1.1.463 with R version 3.5.2.

To investigate the relationship between MSRS, LESS, and Beighton scores, Spearman rank correlation coefficients (ρ) were calculated given the ordinal nature of the data. The correlation coefficient values were interpreted using thresholds of 0.30, 0.50, 0.70, and 0.90 to indicate low, moderate, high, and very high correlations (Mukaka, 2012). Correlations below 0.30 were considered negligible.

Independent *t*-tests with equal variance were conducted to investigate differences in MSRS scores between low and high (LESS ≥ 5 errors) injury risk, and non-hypermobile and hypermobile (Beighton score ≥ 5 points for females and ≥ 4 points for males) participants. Mean differences and 95% confidence intervals [upper, lower] in MSRS scores between groups and corresponding effect sizes (Hedge's *g*) with 95% confidence intervals were calculated. Thresholds for interpreting the magnitude of Hedge's *g* were 0.20, 0.50, and 0.80 for small, medium, and large effects (Lakens, 2013). Effect sizes below 0.20 were considered trivial. There were no missing data, so data from all 60 participants were analyzed. Note that analysis of each MSRS subscale (Conscious Motor Processing and Movement Self-Consciousness) separately yielded similar results.

3. Results

The mean MSRS score for all participants was 37.9 ± 8.3 points (range: 19 to 54). Mean LESS score was 5.3 ± 1.5 errors (range: 2.0 to 9.7). The median and interquartile range of Beighton score for all participants was 2.5 (4.0) points (range: 0 to 9).

There was a negligible non-significant relationship between MSRS and LESS scores ($\rho = 0.06$, $p = 0.625$) and MSRS and Beighton scores ($\rho = 0.09$, $p = 0.481$). The MSRS scores between participants at low and high injury risk were similar (Table 2). There was no significant difference in MSRS scores between non-hypermobile and hypermobile participants, with a trivial effect of grouping on MSRS scores (Table 2).

4. Discussion

The purpose of our study was to investigate the relationship between MSRS, LESS, and Beighton scores, and to compare MSRS scores between high and low injury risk participants and between non-hypermobile and asymptomatic hypermobile participants. In our cohort, there was no significant relationship between MSRS, LESS, and Beighton scores, and no difference in MSRS scores between the subgroups analyzed. The results indicate that participants with greater propensity for conscious monitoring and control of their movements do not present with a greater number of high injury risk movement patterns during double-leg jump-landing as assessed by the LESS and propensity for movement specific reinvestment does not vary in asymptomatic hypermobile individuals compared to non-hypermobile individuals.

The lack of an association between injury risk according to LESS scores and movement specific reinvestment could be due to the phylogenetic nature of the LESS task, the manner in which reinvestment occurs, the low-pressure testing environment, or a combination of these factors. Unlike ontogenetic skills, which require people to learn them, phylogenetic skills (such as jumping) typically can be performed by anyone who is healthy, with minimal conscious processing (Masters & Poolton, 2012). Consequently, phylogenetic skills tend to be less susceptible to disruption by conscious control (reinvestment) than ontogenetic tasks (Masters & Poolton, 2012), which would mitigate differences between high and low MSRS scores. Previous studies have also confirmed an association between high propensity for movement specific reinvestment and poorer sport-specific task performance under psychological pressure (Chell et al., 2003; Jackson et al., 2006; Maxwell et al., 2006). Specifically, individuals with high MSRS scores displayed greater susceptibility to skill failure during soccer kicking (Chell et al., 2003), golf putting (Maxwell et al., 2006), and field-hockey dribbling (Jackson et al., 2006) under high pressure situations. These ontogenetic skills are seldom automated to the same extent as phylogenetic skills, so they require considerable concentration to be performed correctly and their execution is easily processed consciously. Psychological pressure amplifies the likelihood that performers (especially high reinventors) will process their movements consciously to ensure that their performance remains effective, but often this 'overthinking of movement' can disrupt fluid movement (Baumeister, 1984; Beilock & Carr, 2001; Gray, 2004; Masters, 1992). The double-leg jump-landing task tested by the LESS requires participants to jump horizontally from a 30-cm high box to a line placed at 50% of their body height, and immediately jump upward as high as possible upon landing. The

Table 2: Comparison of MSRS scores between groups in the sampled cohort (n = 60).

	n	MSRS scores (points)	MD [95% CI]	*t*-test	Hedge's *g* [95% CI]
At low risk [a]	21	37.8 ± 7.8	-0.2	0.933	-0.02
At high risk [a]	39	38.0 ± 8.6	[-4.7 to 4.3]		[-0.56 to 0.51]
Non-hypermobile [b]	41	37.5 ± 8.9	-1.5	0.524	-0.18
Hypermobile [b]	19	39.0 ± 7.0	[-6.1 to 3.2]		[-0.72 to 0.37]

Abbreviations: *n*, number of participants; MSRS, Movement Specific Reinvestment Scale; MD, mean difference; CI, confidence interval.
[a] At low risk Landing Error Scoring System (LESS) scores < 5 errors; at high risk LESS scores ≥ 5
[b] Hypermobile, Beighton score ≥ 5 points for females and ≥ 4 points for males; non-hypermobile, Beighton score < 5 points for females and < 4 point for males.

task involves movements that are presumably highly automated, so it requires minimal concentration and cannot easily be processed consciously. Thus, performance of the task is less likely to be influenced by movement specific reinvestment. Furthermore, the LESS testing environment imposes minimal pressure to perform well. Participants are not informed of the LESS scoring criteria when they perform the test and receive no performance feedback that might reveal innate movement patterns linked with a higher risk of sustaining non-contact lower-body and ACL injuries. As such, participants therefore are unaware of what characterizes good LESS performance or whether they are performing well (or not). Results might have been different with presence of an overhead target given that it can act as an external motivator and performance indicator, thereby altering movement patterns (Ford et al., 2005; Ford, Nguyen, Hegedus, & Taylor, 2017). Injury-risk and propensity for conscious monitoring and control of movement may be related under certain circumstances, with the association only surfacing in cases where participants are highly motivated to perform successfully (e.g., under pressure) or when they are aware of what constitutes successful or unsuccessful performance. Future research should examine this possibility by testing biomechanics during demanding high-injury risk sport-specific tasks under psychological pressure similar to the competition environment. Only once such investigations are completed will it be possible to reach conclusions about the potential role of movement specific reinvestment in sport-related injuries.

The theory of reinvestment proposes that, in addition to psychological pressure, a variety of other contingencies can cause a person to direct attention to conscious movement processing. These include instructions, novel task demands, boredom, and performance errors (Masters & Maxwell, 2008). For the purposes of LESS task standardization, participants received several instructions during testing. The instructions were to jump off the box with both feet, land in front of the designated line, and jump as high as possible upward upon landing (Padua et al., 2009). However, these instructions are unlikely to cause participants to direct their attention towards the mechanics of their movements; indeed, the instruction to jump upward for maximal vertical height is important in LESS testing because it shifts participants' focus towards performance rather than landing mechanics (Padua et al., 2009). Consequently, focusing externally on movement outcomes, in this case on the height of the jump, rather than internally on the movements is likely to have distracted attention away from the movement biomechanics, thereby reducing the likelihood of movement specific reinvestment (Maxwell et al., 2006; Wulf, Weigelt, Poulter, & McNevin, 2003).

With progressing age, degenerative changes affect all body systems and often result in pain, fatigue, muscle weakness, sensory deficits, poor balance, cognitive deficit, and other comorbidities, which are common in the elderly population (Schultz, 1992). All of these signs and symptoms impair mobility and make every movement challenging (Schultz, 1992). It may be that elderly people with movement impairment consciously process movement to avoid pain, falls, or trauma. Increased reinvestment may lead to disturbed movement patterns and greater injury risk compared to low reinvestors, similar to elder fallers who scored significantly higher than non-fallers on the MSRS (Wong et al., 2008). Therefore, it is possible that an association between MSRS scores and injury risk exists and should be further explored in the older population. Furthermore, severity of movement impairment may be positively associated with MSRS scores given that propensity for reinvestment has been shown to be greater in people with stroke compared to age-matched controls (Orrell et al., 2009), and to be positively associated with duration of Parkinson's disease (Masters et al., 2007). Disorder of connective tissue and excessive joint movement increase the likelihood of macro and micro traumas to the musculoskeletal system, which in turn lead to acute and persistent pain, early joint osteoarthrosis, and loss of function in hypermobile individuals (Castori et al., 2017; Tinkle et al., 2017). For instance, hypermobile individuals present with a higher degree of joint osteoarthrosis earlier in life compared to non-hypermobile peers (Tinkle et al., 2017). Therefore, the hypermobile population may present with greater movement impairment and associated pain earlier in life, which may lead to greater conscious processing of movements compared to non-hypermobile age-matched individuals. However, there is no supporting evidence currently available to support or refute that elder hypermobile individuals consciously process movements to a greater extent compared to age-matched non-hypermobile individuals.

The asymptomatic hypermobile participants tested in our study did not exhibit higher MSRS scores compared to non-hypermobile participants. The framework for the classification of joint hypermobility (Castori et al., 2017) used in our study suggests categorising hypermobile individuals as (1) those with asymptomatic joint hypermobility, (2) those with a well-defined syndrome associated with joint hypermobility (e.g., Ehlers Danlos syndrome and Marfan syndrome), and (3) those with symptomatic joint hypermobility. Studies exploring injury risk and anxiety in hypermobile individuals have not differentiated between joint hypermobility groups according to this classification (Dallinga et al., 2012; Donaldson, 2012; Pacey et al., 2010), with most previous studies exploring movement of hypermobile individuals involving children (Fatoye et al., 2011; Junge et al., 2015), symptomatic individuals (Simonsen et al., 2012), or individuals with well-defined disorders (Galli et al., 2011; Rombaut et al., 2011). Based on our knowledge, a single study has involved asymptomatic hypermobile individuals (Luder et al., 2015). In this study, symptomatic hypermobile females showed significantly lower EMG activity for the quadriceps during stair climbing compared to females with normal mobility; however, the EMG activity of asymptomatic hypermobile females did not differ from controls. These results indicate that there may be some clinically relevant differences in neuromuscular control and muscle recruitment patterns between asymptomatic and symptomatic hypermobile individuals that require further exploration. It is possible that our sample of asymptomatic hypermobile individuals adapt to their condition and use strategies to actively stabilize their hypermobile joints during dynamic tasks, which may explain to some extent why they do not suffer from chronic pain and other symptoms typically associated with hypermobility. Therefore, it may be that the asymptomatic hypermobile individuals tested in our study presented with similar injury risk, prevalence for anxiety, and movement control compared to our non-hypermobile individuals, which would explain the lack of significant differences between hypermobile and non-hypermobile participants in terms of MSRS scores. Furthermore, symptoms associated with symptomatic hypermobility (e.g., chronic pain or fatigue) potentially play a more important role in injury risk and be more strongly associated with MSRS scores compared to hypermobility itself. Therefore, we recommend that future research explores the MSRS in symptomatic hypermobile individuals and individuals with well-defined syndromes associated with joint hypermobility to fully elucidate whether or not conscious monitoring and control of movement plays a role in injury risk or movement control of hypermobile individuals.

Based on our results, propensity for movement specific reinvestment was not significantly associated with injury risk assessed by the LESS, which may be due to the phylogenetic nature of the LESS task and the low-pressure testing environment. Examining the influence of reinvestment on the biomechanics of demanding sport and injury specific tasks under psychological pressure similar to a competition environment is needed to determine whether reinvestment-specific interventions may assist injury prevention efforts. Participants with asymptomatic generalized hypermobility did not present with significantly different MSRS scores compared to non-hypermobile participants. Examination of the MSRS in symptomatic hypermobile individuals and individuals with well-defined syndromes is needed to elucidate whether or not conscious monitoring and control of movement plays a role in these conditions. This information would inform clinical practice and whether implementing motor learning strategies that discourage the propensity for reinvestment is of potential benefit during the rehabilitation process in these population groups.

Conflict of Interest

The authors declare no conflict of interests.

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The effects of unilateral hand contractions on conscious control in early motor learning

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ABSTRACT

Hemisphere asymmetry can be influenced by hand contractions. Brain imaging studies have indicated that pre-performance left-hand contractions may reduce verbal-analytical engagement in motor planning, whereas pre-performance right-hand contractions may increase verbal-analytical engagement in motor planning. This study examined whether a pre-performance left-hand contraction protocol reduced verbal-analytical engagement during practice of a golf putting task, thereby causing implicit motor learning. Forty-eight golf-novices were randomly allocated to left-hand contractions, right-hand contractions or no hand-contractions (control) groups. A line bisection task was conducted as a manipulation check of whether hemisphere asymmetry occurred. All participants practiced a golf putting task, with their allotted hand contraction protocol performed for 30 sec before every ten putts. Thereafter, participants completed two retention tests (blocks of single-task putting) before and after one transfer test (a block of dual-task putting). Different objective and subjective measures of verbal-analytical engagement were collected. Golf putting accuracy and kinematics were assessed. Additionally, mood-state as a function of hemisphere asymmetry was measured. The line bisection task did not reveal a hemisphere asymmetry effect of the different hand contraction protocols. All groups equally improved during practice; however, the no hand-contraction (control) group showed better performance during both retention tests compared to left-hand and right-hand contraction groups. All groups performed worse in the dual-task transfer test. The objective and subjective measures of verbal-analytical engagement revealed no effect of hand contractions. General mood-state decreased for all groups from pre- to post-practice. Unilateral hand contractions prior to practicing the golf-putting task did not affect performance differently from the no hand-contraction (control) group. However, hand contractions resulted in worse performance compared to the no hand-contraction group during the retention tests, and dual-task transfer performance disrupted performance in all groups. No differences in verbal-analytical engagement were evident. Consequently, left-hand contractions did not promote implicit motor learning. Possible explanations and recommendations for future studies are discussed.

1. Introduction

Pre-performance unilateral hand contraction protocols have been revealed to cause hemispheric asymmetry (Gable, Poole, & Cook, 2013; Harmon-Jones, 2006; Peterson, Shackman, & Harmon-Jones, 2008; Schiff, Guirguis, Kenwood, & Herman, 1998). Contralateral couplings between the hands and the brain mean that left-hand contractions activate the right hemisphere and suppress the left hemisphere, whereas right-hand contractions activate the left hemisphere and suppress the right hemisphere. Beckmann, Gröpel, and Ehrlenspiel (2013) and Gröpel and Beckmann (2017) showed that left-hand contractions prior to skill execution led to better motor performance under pressure compared to right-hand contractions among semi-professional athletes. The left hemisphere of the brain is known to be responsible for verbal-analytical processes, whereas the right hemisphere is responsible for visual-spatial processes (De Renzi, 1982), so Beckmann et al. (2013) suggested that better performance under pressure was a consequence of left-hand contractions suppressing the left hemisphere and thus suppressing disruptive verbal-analytical

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processes. Verbal-analytical processes have been linked to conscious control of movement (e.g., Gallicchio, Cooke, & Ring, 2016; Zhu, Poolton, Wilson, Maxwell, & Masters, 2011), which is associated with disrupted motor performance under pressure (e.g., Masters & Maxwell, 2008; Zhu et al., 2011).

Hoskens, Bellomo, Uiga, Cooke, and Masters (2020) were the first to use cortical activity to investigate whether pre-performance unilateral hand contraction protocols influenced verbal-analytical engagement in motor planning during a golf putting task. Verbal-analytical engagement in motor planning is thought to influence cortical synchronization (i.e., EEG connectivity) between the verbal left temporal (T7) and the motor planning mid-frontal (Fz) locations on the scalp in the final seconds before and during movements (e.g., Gallicchio et al., 2016; Zhu et al., 2011). Hoskens et al. (2020) revealed that pre-performance left-hand contractions resulted in lower T7-Fz connectivity during performance of a golf putting task compared to right-hand and no hand-contraction protocols, and this was interpreted to indicate reduced verbal-analytical engagement in motor planning during performance. Furthermore, pre-performance right-hand contractions caused increased T7-Fz connectivity, which may indicate greater verbal-analytical engagement compared to left-hand contractions or no hand-contractions.

Based on the findings of Hoskens et al. (2020), this study examined whether left-hand contraction protocols have potential to cause implicit motor learning by reducing verbal-analytical engagement during motor planning. In contrast to explicit motor learning, implicit motor learning is designed to minimizes verbal-analytical processes during movement planning and execution by specifically reducing the amount of verbal-analytical knowledge that a performer can access explicitly (e.g., Masters, 1992; Masters & Maxwell, 2004; Maxwell, Masters, & Eves, 2003). It has been claimed that implicit processes are more efficient at guiding movements and result in robust performance under pressure compared to explicit processes (Masters, 1992; Masters, van Duijn, & Uiga, 2019). Different approaches have been established to promote implicit motor learning. Masters (1992) asked people practicing a golf putting task to also carry out a secondary task (continuously generating random letters of the alphabet in time with a metronome). The secondary task used up resources normally available to process information about the putting task, so participants learned implicitly. Maxwell, Masters, Kerr, and Weedon (2001) reduced the amount of errors during golf putting practice by starting from close to the target and then gradually moving further away in increments of 25cm. Maxwell et al. (2001) found that reducing the amount of errors during practice lowered the likelihood that participants would use verbal-analytical processes to consciously improve their performance, presumably because they were successful. Zhu et al. (2015) used cathodal (i.e., inhibitory) transcranial direct current stimulation (tDCS) to reduce activity in the left dorsolateral prefrontal cortex (DLPFC), which is associated with working memory processes and verbal learning mechanisms (Brunoni & Vanderhasselt, 2014). Zhu et al. (2015) found evidence of suppressed verbal-analytical engagement during movement planning and execution, reflective of implicit motor learning.

Here we examine whether a pre-performance left-hand contraction protocol can be used to promote implicit motor learning by suppressing verbal-analytical engagement in the task and thereby minimizing accumulation of explicit knowledge. Three groups of participants practiced a golf putting task. Prior to each block of trials, participants completed left-hand contractions, right-hand contractions or no hand-contractions. Similarly to Goldstein, Revivo, Kreitler, and Metuki (2010) a line bisection task was used as a manipulation check of whether hand contractions caused hemispheric asymmetry.[1] After a recovery interval they completed a test phase, which consisted of two retention tests separated by a dual-task transfer test. The retention tests were used to establish effects on performance (mean radial error) after boredom and fatigue had abated. The dual-task transfer test was used as an indicator of implicit motor learning. Explicitly learned motor tasks are typically disrupted by a secondary task that requires verbal-analytical processing, because performance of the motor task also requires verbal-analytical processing. Implicitly learned motor tasks, on the other hand, are not disrupted by a secondary task that requires verbal-analytical processing, because performance of the motor task does not require verbal-analytical processing (e.g., Maxwell, et al., 2001). Subjective and objective measures of technique change during practice were also used to assess whether hand contraction protocols influenced verbal-analytical engagement in performance. Changes in technique are associated with verbal-analytical engagement in performance as people test hypotheses in a search for motor solutions (Maxwell et al., 2001; Maxwell, Masters, & Poolton, 2006). Additionally, following the first retention test, participants were asked to recall the final position of the ball on each trial. We speculated that participants would have better recall if they had been using verbal-analytical processes to consciously test hypotheses based on the outcomes of putts on previous trials.

Finally, measures of general and motor related mood-states were assessed prior to and after golf putting practice to control for conflicting mood states that may have been caused by the hand contraction protocols.[2]

Our primary interest was in the effects of hand contractions on motor learning. We predicted that left-hand contractions, which raise activity in the right hemisphere and lower activity in the left hemisphere, would reduce verbal-analytical engagement in movements during practice of a golf putting task, thus promoting

[1] In most people, attention is spatially biased to the left, which causes them to judge the center of a horizontal line to be more to the left than the right (for a review see, Jewell & McCourt, 2000). This phenomenon, pseudoneglect (Bowers & Heilman, 1980), is thought to occur because the right hemisphere of the human brain is dominant for spatial attention processes (e.g., Roberts & Turnbull, 2010; Turner, Hahn, & Kellogg, 2017) and is strongly connected with the contralateral hemispace (e.g., Corbetta, Miezin, Shulman, & Petersen, 1993). If hand contraction protocols influence hemisphere activity, they should influence spatial bias. Goldstein et al. (2010), for example, revealed that left-hand contraction protocols resulted in greater bias to the left in the line bisection task, whereas right-hand contractions resulted in greater bias to the right.

[2] The 'valence hypothesis' suggests that the left hemisphere is associated with positive emotions, whereas the right hemisphere is associated with negative emotions (see Davidson, 1992, for a review). Consistent with the 'valence hypothesis', evidence suggests that right-hand contractions promote more positive emotions (i.e., higher left hemisphere activity) but left-hand contractions promote more negative emotions (Propper, Dodd, Christman, & Brunye, 2017; Schiff & Lamon, 1994; Schiff & Truchon, 1993).

implicit motor learning. We therefore expected left-hand contractions to result in fewer self-reported technique changes, lower kinematic variability in technique (reflective of less hypothesis testing), worse recall of performance outcome and better performance on a dual-task transfer test compared to right-hand and no hand-contractions.

2. Methods

2.1 Participants and Design

Forty-eight people were recruited to participate in this study (Mean age = 24.46 years, SD = 5.85 years, 26 female). All participants had normal/corrected vision and self-reported being right-hand dominant. A between subjects design was adopted, with the participants randomly allocated to a left-hand contractions, right-hand contractions or no hand-contractions (control) group. Participants completed a practice phase followed by a test phase (see *Procedure*). The study received ethical approval from the University Human Research Ethics Committee.

2.2 Task

The hand contraction protocols required participants to firmly contract a stress ball at a self-paced rate either with their left hand or right hand. In the no hand-contraction (control) group, participants placed their hands in their lap and held them still.

The golf putting task consisted of hitting a regular-size golf ball (4.7 cm diam.) to a target on an artificial grass surface, using a golf putter (80 cm length) (see Figure 1.A). The target (a 12 cm diam. black circle) was positioned 1.9 m from the starting position. We used a flat target instead of the traditional golf putting hole in order to yield precise measures of performance, in terms of both accuracy (i.e., mean radial error) and directional bias (i.e., directional error) (see Figure 1.B). The SAM PuttLab system (SAM PuttLab, Science motion GmbH, Munich, Germany, www.scienceandmotion.de), with an overall sampling rate of 210 Hz, was used to obtain kinematics of the putter (SAM PuttLab reports manual, 2010).

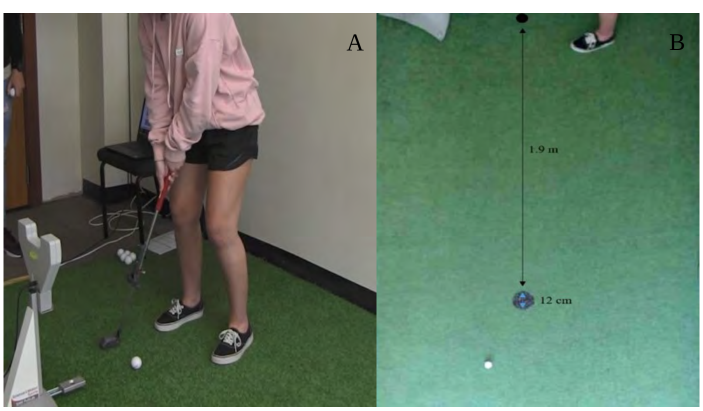

Figure 1: Experimental set up of the golf putting task. A) SAM PuttLab set up B) dimensions of the target.

2.3 Measures

2.3.1 Line bisection – Manipulation check

The line bisection task was conducted prior to and after a single pre-practice hand contraction protocol before motor practice, and once after motor practice, to confirm whether hand contractions influenced hemispheric asymmetry, which would result in greater leftward bias for left-hand contractions and greater rightward bias for right-hand contractions (e.g., Goldstein et al., 2010; Jewell & McCourt, 2000).

The line bisection task required participants to mark the exact middle of two straight horizontal lines (18 cm length) presented consecutively on a sheet of paper. The lines were offset either to the left or to the right on the sheet of paper (Goldstein et al., 2010). Deviation from the middle point of the line (i.e., 9 cm) was calculated as percentage bias error (Scarisbrick, Tweedy, & Kuslansky, 1987). The mean percentage bias error of the two trials was computed. Positive scores reflect prejudice to mark further to the right side of the line, suggesting increased left hemisphere activation, whereas negative scores reflect prejudice to mark further to the left side suggesting increased right hemisphere activation (Goldstein et al., 2010).

2.3.2 Measures of verbal-analytical engagement in the putting task

Self-reported technique changes: Following the practice phase, participants answered questions related to technique changes (i.e., 'I tried different ways of hitting the target' and 'I changed my technique while doing the golf-putting task'). The items were rated on a 6-point Likert Scale ranging from 1 (strongly disagree) to 6 (strongly agree). The mean score of both questions was taken.

Kinematics: Golf putting swing kinematics were computed to provide insight into technique changes during practice phase and the test phase (e.g., Maxwell et al., 2003). The kinematics obtained from the SAM PuttLab data were standard deviation (SD) of the putter velocity at impact (mm/sec) and putter face angle at impact (degrees) (see, Malhotra, Poolton, Wilson, Omuro, & Masters, 2015).

Performance outcome recall: Following the first retention test, participants were asked to recall the general dispersion of their putts by indicating the number of putts that had come to rest in each area of a diagrammatic representation of the target area (see Figure 2). Recall performance was calculated as the absolute difference between the reported numbers and the actual number of balls in each area.

Golf putting performance: Three performance scores – radial error (cm), directional error (cm) and short/long error (cm) – were computed for each golf putt, using ScorePutting software (written in National Instruments LabVIEW), which uses photographs from a camera placed directly above the putting target (Neumann & Thomas, 2008).

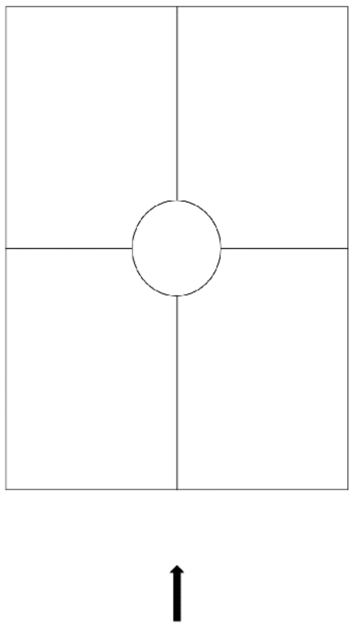

Figure 2: Recall sheet

2.3.3 Mood-state

Overall mood-state was measured prior to and after golf putting practice, using one question (i.e., 'overall, my mood at the moment is'), which was rated on a Likert-type scale ranging from -10 (very unpleasant) to 10 (very pleasant).

2.4 Procedure

Participants were informed about the context of the study, signed an informed consent form and completed the demographics and overall mood-state questionnaires prior to the start of the experiment. They then completed the line bisection task before and after performing a single hand contraction protocol for 45 sec (left-hand, right-hand or no hand-contractions). After this, seven blocks of ten golf putting trials were completed, with each block preceded by a 30 sec hand contraction protocol (left-hand, right-hand or no hand-contractions).[3] Upon completion of the 70 trials, participants again completed the line bisection task. The self-report measures of technique changes and of overall mood-state were administered. Finally, following a rest interval (10 min), a test phase was performed. The test phase consisted of a dual-task transfer test (10 trials of putting and tone counting) sandwiched between two retention tests (10 trials of single-task putting each). During the dual-task transfer test, participants heard low (500 Hz) and high (1000 Hz) pitched tones (interval 1000 msec) played through computer software (Labview Application Builder 2010, National Instruments Inc., Austin, TX) in a randomized order. Participants were asked to count the number of low-pitched tones. The absolute deviation between number of tones reported and the number of tones presented was calculated as a performance percentage. After completion of retention test 1, participants were asked to recall the final resting position of each of their putts.

2.5 Statistical Approach

Percentage bias error (i.e., deviation left or right of exact middle, cm) during the line bisection tasks was subjected to a 3 x 3 repeated measures analysis of variance (ANOVA): Group (Left-hand contractions, Right-hand contractions, No hand-contractions) x Test (Pre-practice test 1, Pre-practice test 2, Post-practice test). To determine whether pseudoneglect occurred, we conducted one-sample t tests (critical value 0.00 cm deviation, i.e., exact middle of the line). Self-reported technique changes and performance outcome recall scores were analysed by one-way ANOVA: Group (Left-hand contractions, Right-hand contractions, No hand-contractions). For the practice phase, the SAM PuttLab measures (SD face impact and velocity impact), radial error, directional error and short/long error were subjected to a 3 x 7 repeated measures ANOVA: Group (Left-hand contractions, Right-hand contractions, No hand-contractions) x Block (B1, B2, B3, B4, B5, B6, B7). For the test phase, the SAM PuttLab measures, radial error, directional error and short/long error were subjected to a 3 x 3 repeated measures ANOVA: Group (Left-hand contractions, Right-hand contractions, No hand-contractions) x Test (Retention 1, Dual-task transfer, Retention 2). Tone counting performance during the dual-task transfer test was subjected to a one-way ANOVA: Group (Left-hand contractions, Right-hand contractions, No hand-contractions).

Overall mood-state was subjected to a 3 x 2 repeated measures ANOVA: Group (Left-hand contractions, Right-hand contractions, No hand-contractions) x Test (Pre-practice phase, Post-practice phase).

Sphericity and normality checks were performed and controlled for when needed. When main effects or interactions were found, separate ANOVAs, post-hoc tests (Bonferroni corrected) or polynomial trend analyses were performed. Effect sizes are reported as partial η squared (ηp^2). The statistical tests were performed using SPSS (IBM, version 26.0) computer software. Significance was set at $p = .05$ for all statistical tests.

3 Results

3.1 Line bisection – Manipulation check

No main effects of Group, $F(2,45) = 0.04$, $p = .958$, $\eta p^2 < .01$, or Test, $F(2,90) = 0.66$, $p = .520$, $\eta p^2 = .01$, were revealed for percentage bias error. There was also no Group x Test interaction, $F(4,90) = 0.44$, $p = .777$, $\eta p^2 = .02$ (see Table 1).

Given that there were no Group or Test effects and no Group x Test interaction, we collapsed all bias errors together (*M* deviation = -0.54 cm, SD = 2.39) and conducted a single one-sample *t* test (critical value 0.00 cm; exact middle of line) to establish whether spatial bias was evident. A significant difference from 0.00 cm was not evident, $t(48) = -1.55$, $p = .127$.

[3] We used multiple hand contraction protocols to maintain the effects of the hand contraction protocols on brain activity.

Table 1: Mean and SD percentage bias error in each group by line bisection test.

Group	Left-hand contractions		Right-hand contractions		No hand-contractions	
	M	SD	M	SD	M	SD
Pre-practice test 1 (%)	-0.09	3.72	-0.16	2.28	-0.87	3.39
Pre-practice test 2 (%)	-0.73	4.06	-0.02	3.13	-0.38	3.34
Post-practice test (%)	-0.68	3.34	-1.13	2.25	-0.78	2.12

Note. A negative mean value means a more leftward bias, and positive value a more rightward bias.

3.2 Measures of verbal-analytical engagement

3.2.1 Self-reported technique changes

The mean score on the self-report technique change questions was 4.34 (SD = 1.06) for the left-hand contraction group, 4.22 (SD = 1.09) for the right-hand contraction group and 4.53 (SD = 1.09) for the no hand-contraction group. No main effect of Group was evident, $F(2,47) = 0.34$, $p = .714$, $\eta p^2 = .02$.

3.2.2 Kinematics

Practice phase: The SD of velocity at impact revealed a main effect of Block, $F(4.66,139.64) = 19.50$, $p < .001$, $\eta p^2 = .39$, but no main effect of Group, $F(2,30) = 0.77$, $p = .474$, $\eta p^2 = .05$, or Group x Block interaction, $F(12,180) = 0.26$, $p = .994$, $\eta p^2 = .02$ (see Figure 3). Post-hoc analysis of the Block effect revealed a quadratic trend, ($p < .001$, $\eta p^2 = .63$); SD of velocity at impact decreased sharply over the first blocks of trials and then levelled off.

The SD of face angle at impact revealed a main effect of Block, $F(6,180) = 4.11$, $p = .001$, $\eta p^2 = .12$, but no main effect of Group, $F(2,30) = 0.45$, $p = .643$, $\eta p^2 = .03$, or Group x Block interaction, $F(12,180) = 0.66$, $p = .785$, $\eta p^2 = .04$ (see Figure 4). Post-hoc analysis of the Block effect revealed a linear trend ($p < .001$, $\eta p^2 = .44$); SD of face angle at impact reduced gradually across blocks of trials.

Test phase: SD of velocity at impact did not reveal a significant main effect of Group, $F(2,37) = 2.40$, $p = .105$, $\eta p^2 = .12$, or of Block, $F(1.73,63.93) = 1.16$, $p = .319$, $\eta p^2 = .03$. There was no Group x Block interaction effect, $F(4,74) = 0.15$, $p = .964$, $\eta p^2 = .01$ (see Figure 3).

SD of face angle at impact did not reveal a significant main effect of Group, $F(2,37) = 0.45$, $p = .643$, $\eta p^2 = .02$, or of Block, $F(2,74) = 1.69$, $p = .191$, $\eta p^2 = .04$, and there was no Group x Block interaction effect, $F(4,74) = 0.58$, $p = .677$, $\eta p^2 = .03$ (see Figure 4).

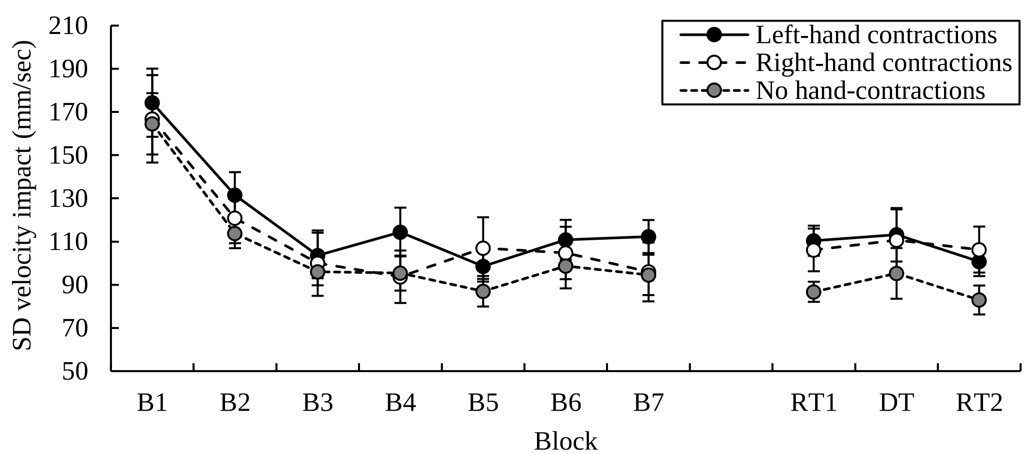

Figure 3: SD of velocity at impact for each block of trials during the practice and test phases, as a function of hand contraction protocol. Error bars represent the standard error of the mean.

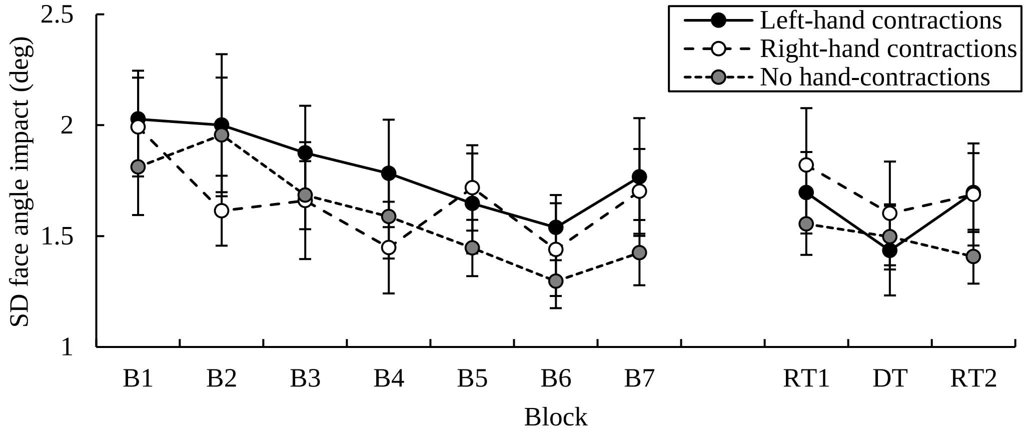

Figure 4: SD of face angle at impact for each block of trials during the practice and test phases, as a function of hand contraction protocol. Error bars represent the standard error of the mean.

3.2.3 Performance outcome recall

Mean recall accuracy was calculated as the number of correctly recalled final ball positions out of the ten trials of retention test 1. Mean recall accuracy was 4.63 (SD = 2.80) for the left-hand contraction group, 5.5 (SD = 1.71) for the right-hand contraction group, and 5.38 for the no hand-contraction (control) group. No main effect of Group was found, $F(2,47) = 0.46$, $p = .635$, $\eta p^2 = .02$.

3.2.4 Golf putting performance

Practice phase: For radial error, a main effect of Block was revealed, $F(6,246) = 28.06$, $p < .001$, $\eta p^2 = .41$, but there was no main effect of Group, $F(2,41) = 1.01$, $p = .375$, $\eta p^2 = .05$, and a Group x Block interaction was not evident, $F(12,246) = 0.63$, $p = .817$, $\eta p^2 = .03$ (see Figure 5). Post-hoc analysis of the Block effect revealed a linear trend ($p < .001$, $\eta p^2 = .76$), suggesting that constant incremental reductions in radial error occurred across blocks of trials.

For directional error, main effects were not evident for Group, $F(2,41) = 0.26$, $p = .771$, $\eta p^2 = .01$, or for Block, $F(6,246) = 1.04$, $p = .399$, $\eta p^2 = .03$, and a Group x Block interaction was not evident, $F(12,246) = 0.99$, $p = .405$, $\eta p^2 = .05$ (see Figure 6).

For short/long error, a main effect of Block was evident, $F(4.78,19581) = 10.19$, $p < .001$, $\eta p^2 = .20$. However, neither a main effect of Group, $F(2,41) = 1.60$, $p = .215$, $\eta p^2 = .07$, nor a Group x Block interaction effect were evident, $F(12,246) = 0.94$, $p = .504$, $\eta p^2 = .04$. Post-hoc analysis of the Block effect revealed a linear trend ($p < .001$, $\eta p^2 = .46$), suggesting that constant incremental reductions in short/long error occurred across blocks of trials (see Figure 7).

Test phase: For radial error, main effects were evident for Group, $F(2,40) = 4.62$, $p = .016$, $\eta p^2 = .19$, and Block, $F(2,80) = 15.87$, $p < .001$, $\eta p^2 = .28$. However, there was not a Group x Block interaction, $F(4,80) = 1.14$, $p = .343$, $\eta p^2 = .05$ (see Figure 5). Post-hoc analysis of the Group effect revealed significantly lower radial error in the no hand-contraction group compared to both the left-hand contraction group ($p = .030$) and the right-hand contraction group ($p = .047$). Radial error did not differ between the left-hand contraction and right-hand contraction groups ($p = 1.00$). Post-hoc analysis of the Block effect revealed significantly greater radial error during the dual-task transfer test, compared to retention test 1 ($p < .001$) and retention test 2 ($p < .001$). Radial error did not differ in the two retention tests ($p = 1.00$).

For directional error, no main effects were evident for Group, $F(2,40) = 0.51$, $p = .605$, $\eta p^2 = .02$, or Block, $F(2,80) = 1.32$, $p = .274$, $\eta p^2 = .03$. There was no Group x Block interaction, $F(4,80) = 0.37$, $p = .829$, $\eta p^2 = .02$ (see Figure 6).

For short/long error, a main effect for Block was revealed $F(1.82,72.88) = 15.85$, $p <.001$, $\eta p^2 = .28$, but there was no main effect of Group, $F(2,40) = 3.00$, $p = .061$, $\eta p^2 = .13$. A Group x Block interaction was not evident, $F(4,80) = 1.49$, $p = .213$, $\eta p^2 = .07$ (see Figure 7). Post-hoc analysis of the Block effect revealed a quadratic trend ($p < .001$, $\eta p^2 = .31$), suggesting that distance errors peaked during the dual-task condition.

3.2.5 Tone counting accuracy

Mean tone counting accuracy was 92% (SD = 0.08%) for the left-hand contraction group, 92% (SD = 0.09%) for the right-hand contraction group and 93% (SD = 0.06%) for the no hand-contraction (control) group. There was no significant difference in tone counting accuracy between groups, $F(2,45) = 0.19$, $p = .828$, $\eta p^2 = .01$.

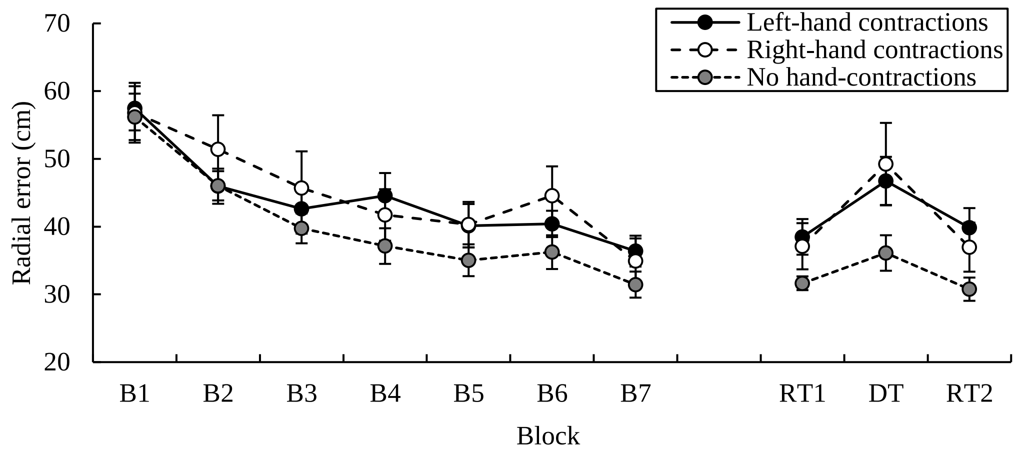

Figure 5: Radial error during each block of trials in the practice phase and the test phase, as a function of hand contraction protocol. Error bars represent the standard error of the mean.

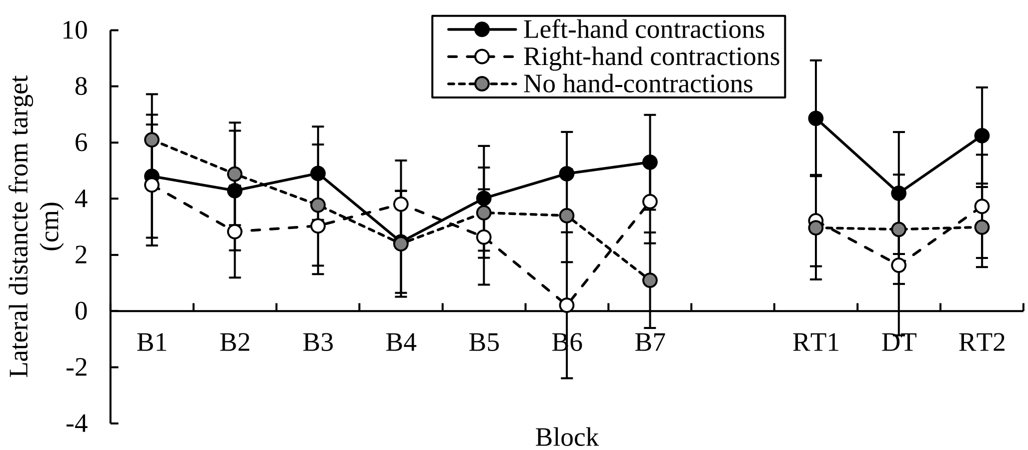

Figure 6: Directional error during each block of trials in the practice phase and the test phase, as a function of hand contraction protocol. Positive values represent putts to the right of the target. Error bars represent the standard error of the mean.

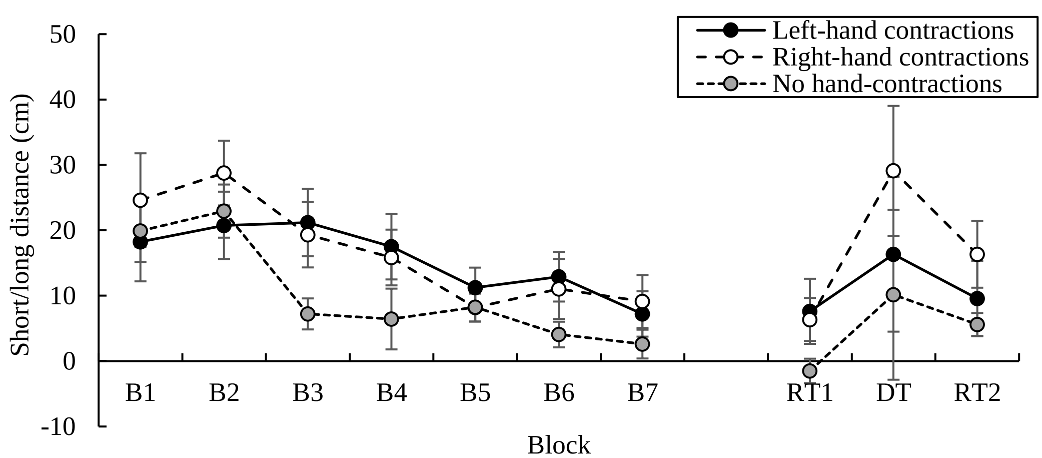

Figure 7: Short/long error during each block of trails in the practice phase and the test phase, as a function of hand contraction protocol. Positive values represent long errors. Error bars represent the standard error of the mean.

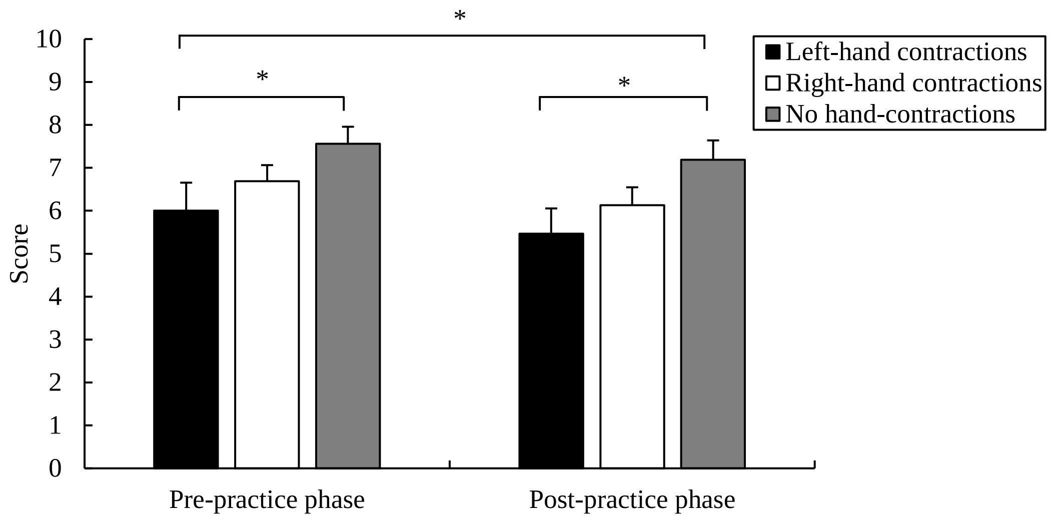

Figure 8: Mean score on the general mood-state question before and after the practice phase, as a function of hand contraction protocol. Error bars represent the standard error of the mean. **p* < .05.

3.3 Mood-state

For overall mood-state, there were significant main effects of Group, $F(2,45) = 3.93$, $p = .027$, $\eta p^2 = .15$, and Test, $F(1,45) = 9.53$, $p = .003$, $\eta p^2 = .18$ (see Figure 8). A Group x Test interaction was not evident, $F(2,45) = 0.14$, $p = .872$, $\eta p^2 = .01$. Post-hoc analysis of the Group effect revealed that overall the left-hand contraction group reported significantly lower mood compared to the no hand-contraction control group ($p = .023$), but the right-hand contraction group did not differ from either of the other groups (p's > .39). Significantly lower mood was evident after the practice phase ($M = 6.10$) compared to before the practice phase ($M = 6.56$) for all groups.

4 Discussion

This study is the first to examine the effects of hand contractions on motor learning. Hoskens et al. (2020) suggested that pre-performance left-hand contractions reduced verbal-analytical engagement in motor planning, so we predicted that left-hand contractions during practice would promote implicit motor learning by reducing explicit processes (e.g., hypothesis testing) that are usually associated with verbal-analytical engagement in performance. However, our measures suggested that there was no effect of hand contraction protocols on verbal-analytical engagement in performance. Self-reported levels of technique change and changes in kinematics (SD of velocity and angle at impact) during the practice phase were not different between the groups. Changes in SD of velocity were consistent with the power law of practice, suggesting that early in practice participants putted the ball with too much or too little force, but attuned quickly to the force (and thus velocity) that was appropriate. Changes in SD of face angle, however, improved gradually throughout practice. Additionally, recall of performance outcome after retention test 1 was not different between groups. Furthermore, no between-group differences in golf-putting performance accuracy (radial error, directional error and short/long error) were evident during the practice phase, with all groups becoming more accurate gradually over blocks. During the test phase, both hand contraction groups demonstrated worse golf-putting performance than the no hand-contraction (control), suggesting that hand contractions interfered with the learning process. Additionally, dual-task putting performance was lower in all three groups compared to single-task performance (both retention tests), suggesting that performance of the golf putting task was equally resource demanding in the groups. The kinematic measures did not change significantly during dual-task performance, however. Possibly, the measures were not sufficiently sensitive to detect change in performance.

One possible explanation for the findings is that the hand-contraction protocols did not induce hemispheric asymmetry. This assumption is supported by the results of the line bisection tasks, which showed that all groups displayed a similar bias when asked to mark the exact middle of the horizontal lines. The results are not consistent with the findings of Goldstein et al. (2010), who revealed greater leftward bias for left-hand contractions. However, our hand contraction protocol differed from other protocols that have been used, raising questions about the impact of timing and duration of hand contractions on hemispheric asymmetry. Other studies have also failed to demonstrate an effect of hand contractions on spatial bias (Baumann, Kuhl, & Kazén, 2005; Moeck, Thomas, & Takarangi, 2019; Propper, McGraw, Brunye, & Weiss, 2013; Turner et al., 2017), so the line bisection task simply may not be a suitable manipulation check in this context.

It is well established that skilled performance is characterised by cortical specificity, with resources gated towards regions that are essential for performance and inhibited in regions that are less essential for performance (e.g., Gallicchio & Ring, 2019; Hatfield & Kerick, 2007; Haufler, Spalding, Santa Maria, & Hatfield, 2000); however, research has shown that this cortical specificity can be reversed under pressure conditions (e.g., Hatfield et al., 2013). Beckmann et al. (2013) demonstrated that pre-performance left-hand contractions, prior to task performance prevented choking under pressure compared to right-hand contractions for semi-professional athletes. Beckmann et al (2013) argued that left-hand contractions might have prevented choking by increasing right hemisphere (visuo-spatial) activity and reducing left hemisphere (verbal-analytic) activity, [4] thereby shifting patterns of cortical activity towards those associated with more automatic performance. For novices, however, optimal patterns of cortical activity may differ or may need to develop over time (Bellomo, Cooke, & Hardy, 2018; Gallicchio, Cooke, & Ring, 2017). Accordingly, the use of pre-performance hand contractions may help to maintain previously established (optimal) patterns of cortical activity in experts but not deliver the same performance-benefits for novices at the initial stages of motor learning. Instead, both right-hand contractions and left-hand contractions may disrupt learning compared to no hand-contractions. Future research should adopt neurological measures (e.g., electroencephalography) to gain more insight into the cognitive processes that are influenced by the hand contraction protocols during practice. Furthermore, adding more practice trials or comparing experts with novices, might reveal whether the hand contraction protocols have a different effect on later stages of learning.

It is also possible that hand contractions may have been distracting or have caused muscle fatigue, which might have interfered with golf putting performance. Alternatively, the influence of left-hand contractions may have been superseded by the activation of the muscles of the right hand during putting because participants used predominantly their dominant hand to power and/or guide their movements. Future research should therefore control for this possibility by utilizing tasks that do not require use of the hands (e.g., soccer penalty kicking).

Participants reported significantly lower overall mood-state following the practice phase, compared to before the practice phase, but this change in mood was similar for all groups, and thus cannot be attributed to a specific hand contraction protocol. This finding is not consistent with Propper et al. (2017) and Schiff and Lamon (1994), who revealed that hand contractions influenced mood-state. Specifically, right-hand contractions resulted in more positive mood-state, presumably as a result of activating the left hemisphere. However, the experiments by Propper et al. (2017) and Schiff and Lamon (1994) did not examine emotional states associated with motor practice, which may explain why the results of our study are not similar. Rather than focus on emotions, studies have increasingly started to examine approach and avoidance behaviour in relation to hemisphere asymmetry (see Kelley, Hortensius, Schutter, & Harmon-Jones, 2017, for a review). This is based on evidence that hemisphere activity is more related to approach or avoidance motivation that might occur to the emotions that are felt (Harle & Sanfey, 2015; Harmon-Jones, Sigelman, Bohlig, & Harmon-Jones, 2003). Consequently, approach and avoidance should be addressed in further studies of hand contraction effects on motor learning, as this might also have an effect on cognitive processes and behaviour during motor learning (e.g., Koch, Holland, & van Knippenberg, 2008; Saarikallio, Luck, Burger, Thompson, & Toiviainen, 2013).

A final limitation is that although we used a study design similar to Zhu et al. (2015), we did not use an appropriately delayed retention test. Delayed retention tests are often conducted after at least a day, allowing effects of practice, such as boredom or fatigue, to fully dissipate, and processes associated with learning to consolidate (e.g., Shea, Lai, Black, & Park, 2000).

To conclude, we found no effect of hand contractions on self-report or objective measures of verbal-analytical engagement by novices when performing golf putting trials. Golf putting performance in the retention tests was worse for both hand contraction groups compared to the no hand-contraction (control) group, and all groups performed worse when asked to carry out a secondary task (tone counting) concurrently with golf putting. Taken together, these initial findings suggest that left-hand contractions are unlikely to promote implicit motor learning. However, given that the study did not include an explicit learning control group and that the manipulation check calls into question whether the hand contraction protocols even had the desired effect on hemisphere asymmetry, we feel that further studies are needed in order to gain a fuller understanding of the potential effect of hand contractions on implicit and explicit motor learning.

Conflict of Interest

The authors declare no conflict of interests.

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[4] Mesagno, Beckmann, Wergin, and Gröpel (2019) have since modified this argument. On the basis of evidence that hand contractions cause cortical relaxation over the entire scalp (Cross-Villasana, Gropel, Doppelmayr, & Beckmann, 2015), they argued that reduced left hemisphere activity following left hand contractions is a function of cortical relaxation in both hemispheres.

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The colour we wear: Impact on self-predicted and actual motor performance

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ABSTRACT

The effect of colour on different aspects of performance has been the subject of substantial research interest, and red had been shown to have varying effects on not only performance, but perceptions as well. This study examined the effect of apparel colour on self-predicted and actual motor performance. Thirty-six young adults (18 females, 18 males; 20.4 SD 1.32 years old), who had no experience in football, performed a task consisting of an agility ladder drill and football shooting, in each of three bib colours (red, blue, black). Self-predicted and actual performances were measured on the dimensions of shooting accuracy and kicking power. A significant effect of colour on self-predicted shooting accuracy was found. Participants expected themselves to shoot less accurately when they were wearing a red bib, compared to when wearing blue and black bibs. No effect of colour on actual performance was found and no significant interaction was found between colour and sex. The findings suggest that wearing red could reduce users' expectations of their performance in a novel motor task; there is no effect on actual performance.

1. Introduction

Colour, as an omnipresent personal experience, influences human cognition, perception and behaviour (Elliot & Maier, 2007; Feltman & Elliot, 2011). Functionally, it has been suggested that colours may attract attention, convey information, or evoke some motivations (Sorokowski et al., 2014). As such, patterns of human responses are expected as a consequence of exposure to specific colours. The majority of relevant research has examined the colour red, thereby generating substantial evidence on the effects of this hue (Jalil, Yunus, & Said, 2012). Red is associated with aggressiveness, power, dominance (Feltman & Elliot, 2011), and higher testosterone levels (Farrelly, Slater, Elliott, Walden, & Wetherell, 2013). Hill and Barton (2005) showed that athletes who wore red attires in boxing, taekwondo and wrestling, had a higher probability of winning during the 2004 Olympic Games. They further showed that the same effect of red found in male athletes was not present in female taekwondo and wrestling athletes. Hence, they argued that wearing the colour red enhances a sense of dominance and triggers superior testosterone responses in those who wear it; thereby enhancing their performance. From an evolutionary perspective, men are suggested to be more sensitive to the effects of red, as this colouration is proposed to be a testosterone-dependent signal of male quality (Ioan et al., 2007).

Attrill, Gresty, Hill, and Barton (2008) extended these findings to team sports, examining English football teams over a 55-year period. They showed that teams wearing red shirts won more games than teams wearing blue, white and yellow-orange shirts. Comparable findings were demonstrated by Piatti, Savage, and Torgler (2012) who analysed Australian Rugby League games over a 30- year period. Focusing on the performance of teams playing at home, they found that teams wearing red shirts were more likely to win compared to teams that wore other coloured shirts. On the other hand, research in European football leagues revealed that wearing red attires did not increase the likelihood of winning compared to wearing other colours (Garcia-Rubio, Picazo-Tadeo, & Gonzalez-Gomez, 2011; Kocher & Sutter, 2008). Such inconsistent findings could be explained by uncontrolled differences that might be expected of studies based on archival data. Further investigations are warranted to better understand the impact of apparel colours on sports-related motor performance.

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Viewed colour also influences attitudes and behaviours of others towards the individuals wearing them (Feltman & Elliot, 2011). For example, goalkeepers in a simulation task reported lower expectancies of saving penalties when penalty takers were wearing red than when they were wearing white (Greenlees, Leyland, Thelwell, & Filby, 2008). In addition, penalty takers scored fewer penalties when facing goalkeepers wearing red compared to those wearing blue and green (Greenlees, Eynon, & Thelwell, 2013). Even viewers appear to be affected, as referees and spectators with high understanding of football rules reportedly judged tackles from behind more harshly when players were wearing red (Hagemann, Strauss, & Leissing, 2008; Krenn, 2014). More recently, viewers perceived treadmill runners to be faster when wearing red compared to when wearing blue (Mentzel, Schücker, Hagemann, & Strauss, 2019). Nevertheless, the evidence has not been conclusive. For instance, Furley, Dicks, and Memmert (2012) found that goalkeepers' perceptions of penalty takers' performance were not affected by the colour of attire (i.e., red vs. white) they were wearing.

Some researchers have proposed that the effects of colour simply reflect culture and sport-specific associations. Greenlees and colleagues (2008) argued that the most successful football teams in England typically wear red, which may have formed associations between red and successful performances. Other researchers, have proposed that certain outfit colours (taking into consideration saturation, brightness, contrast) can affect the visibility of the opponent, thereby influencing performance (Rowe, Harris, & Roberts, 2005). Specifically, they showed a disadvantage for judo athletes wearing white compared to athletes wearing blue. Rowe et al. (2005) argued that a white judogi is likely to be perceived as brighter so moves can therefore be more easily anticipated. However, Dijkstra and Preenen (2008) argued that such an effect tends to be a result of several confounding factors associated with retrospective study designs, such as dissimilar prior experiences of participants, recovery time differences and the seeding system (i.e., the first called athlete for the fight used to wear a blue judogi). Consequently, more conclusive evidence from study designs that are not retrospective is needed.

Experimental study designs that examined uni-dimensional measures of performance have explored the mechanisms underlying the effects of colour. Most manipulations have been in terms of viewed colours (i.e., colour of environment rather than of apparel), and findings have been inconsistent. For example, grip strength was enhanced after viewing red hues but not after viewing other colours, such as blue, pink, and grey (Crane, Hensarling, Jung, Sands, & Petrella, 2008; Elliot & Aarts, 2011). However, exposure to a red environment (compared to blue and green) resulted in experienced cyclists' poorer performance as evident in shorter distances cycled, and less reported enjoyment of cycling (Briki, Rinaldi, Riera, Trong, & Hue, 2015). A further inconsistency is that Araki and Huddleston (2002) found that the colour of the target (i.e., blue, green, red, white) had no effect on dart throwing performance. Additionally, albeit with a small sample size, one study examined testosterone responses between cyclists who wore red or black apparel when cycling to exhaustion; no significant differences between groups were found (Hackney, 2006). Taken together, these inconclusive findings suggest that the effect of colour on different aspects of performance requires further examination.

Evidence on the effects of the colour that people wear on motor performance potentially adds to the range of strategies that could be employed to enhance performance in different sports contexts. Research, however, has been mostly focused on the influence of red hues on sports performance outcomes (i.e., winning). Evidence that relates to output other than likelihood to win is inconsistent, and there continues to be limited information that is specific to motor performance. To contribute towards clarifying the state of evidence, the current study sought to examine the effect of colour on two dimensions of football kicking performance – accuracy and power. Noting that the colour red is associated with perceptions of threat and dominance (Feltman & Elliot, 2011), self-predicted performance was also measured. Using a football drill task, we manipulated the colour of participants' apparel. In conditions where participants wore apparel in the chromatic colours of red and blue and the achromatic colour of black, we compared participants' self-predicted and actual performance of the football drill execution. We hypothesized that the colour of apparel would influence participants' self-predicted and actual performance. Specifically, we expected red to have a relative enhancing effect on self-predicted and actual performance.

2. Methods

2.1. Participants

A priori calculation using GPower 3.1.9 (Faul, Erdfelder, Lang, & Buchner, 2007), based on an effect size of $\eta 2 = 0.31$ (Dreiskaemper, Strauss, Hagemann, & Busch, 2013), with power set at 0.95 and alpha at 0.05, revealed a desired sample size of 30 participants. With an additional 20% increase in the target sample size, 36 undergraduate students were recruited to participate in this study (18 females, 18 males; Mean age = 20.4, s.d. = 1.32 years). All the participants were novices to the task and had no experiences with football drills or training. Participants were also screened for the following exclusion criteria: (a) lower extremity injuries within the last six months prior to the study, (b) motor and/or cognitive disorders, and (c) colour blindness (i.e., using the Ishihara Colour Blindness Test).

2.2. Procedures

All study procedures were reviewed and approved by the institutional ethics review committee. Participants signed informed consent forms prior to any procedure. In order to promote continuous motivation in task performance, participants were informed that a monetary reward was on offer for the top five performers in shooting accuracy.

Participants were asked to watch a one-minute instructional video of the task that they were to perform. The video featured a model wearing white apparel, who performed an icky shuffle agility ladder drill, followed by shooting a stationary football towards the marked centre of a goal. The agility ladder drill was included to enhance the ecological validity of the task. Participants were instructed to move through the ladder quickly, then kick the ball and hit the target as accurately as possible. All participants were able to perform the task successfully after one practice trial. Four test trials were performed while wearing each of three colours of bibs (red, blue and black), with the colour sequence counter-balanced across participants.

With each bib colour, participants gazed at themselves in a full body size mirror for 30 seconds to call attention to the colour manipulation. They were then asked to predict their level of performance in terms of shooting accuracy and kicking power, using a Visual Analogue Scale (VAS; Cline, Herman, Shaw, & Morton, 1992). This was followed by performance of the football task according to the video instructions. Upon completing four trials, participants took a two-minute break while still wearing their bib. They were then asked to change to the next counter-balanced bib colour and the same procedure was repeated until all three colours were worn (i.e., 12 test trials).

2.3. Equipment and set-up

Lighting in the laboratory setting was controlled and curtains were used to cover the natural light, ensuring that all participants were exposed to the same gradient of colours and lighting in the background. The set-up (see Figure 1) consisted of a 10-box agility ladder (300 cm in length), a size 5 football placed on a kicking tee 250 cm from the goal, and a standardized futsal goal (200 cm x 300 cm; Fédération Internationale de Football Association, FIFA). A kicking target, represented by a 10 cm x 10 cm cross, was set at the centre of the goal and 90 cm above ground.

Self-predicted performances for shooting accuracy and kicking power were measured using VAS for each performance dimension. This is deemed a valid and reliable subjective measurement of a psychological construct using interval level data (Cline et al., 1992), and is particularly suitable when each question is along a single dimension (Rausch & Zehetleitner, 2014). The VAS used was an unmarked 10-cm line with descriptors at each end, and participants were asked to draw a vertical line on the scale to indicate how well they expected to perform. For accuracy, the descriptors were 0 cm “farthest from target possible” and 10 cm “absolutely on target”; for perceived power, 0 cm “absolutely no power” and 10 cm “strongest power possible”. Marks were subsequently measured in cm and converted to percentage based on the full measure of 10 cm (100%). Marks closer to 10 cm represented better self-predicted performance.

A ceiling mounted camcorder (GoPro, Hero 4 Silver Edition, 60fps 720p) recorded the point of contact of the football relative to the target. The camera was located perpendicular to the goal, at a distance of 500 cm, and at a height of 90 cm above ground. Post-hoc video analysis using Adobe Illustrator CS4 (Adobe Inc., San Francisco, CA, USA) was performed to quantify kicking accuracy. The absolute error from target was measured in cm; smaller figures represented greater accuracy. A speed gun (Bushnell, Outdoor Technology Velocity Speed Gun 101911) was used to measure the velocity of the kicked ball (km/hr) as a measure of power; higher velocity represented greater explosive force contraction (Hermassi, Chelly, Fathloun, & Shephard, 2010).

2.4. Data analysis

The Shapiro-Wilk test showed that all perceived and actual performance scores were normally distributed (all $p > 0.05$). To examine the effect of bib colour on self-predicted performance, 3 (red, blue, black) x 2 (male, female) multivariate repeated measures analysis of variance (RM-ANOVA) was conducted on the average VAS scores (out of four trials) for accuracy and power. To examine the effect of bib colour on actual performance, 3 (red, blue, black) x 2 (male, female) RM-ANOVA was conducted separately on the average performance scores (out of four trials) for accuracy and power. Mauchly’s test confirmed that the sphericity assumption was not violated across all variables (all $p > 0.05$). Significant main effects were followed up by univariate repeated measures ANOVA and paired samples t-tests with Bonferroni correction. Statistical significance was $p < 0.05$ ($p < 0.017$ for Bonferroni correction); tests were performed using SPSS 25.0.

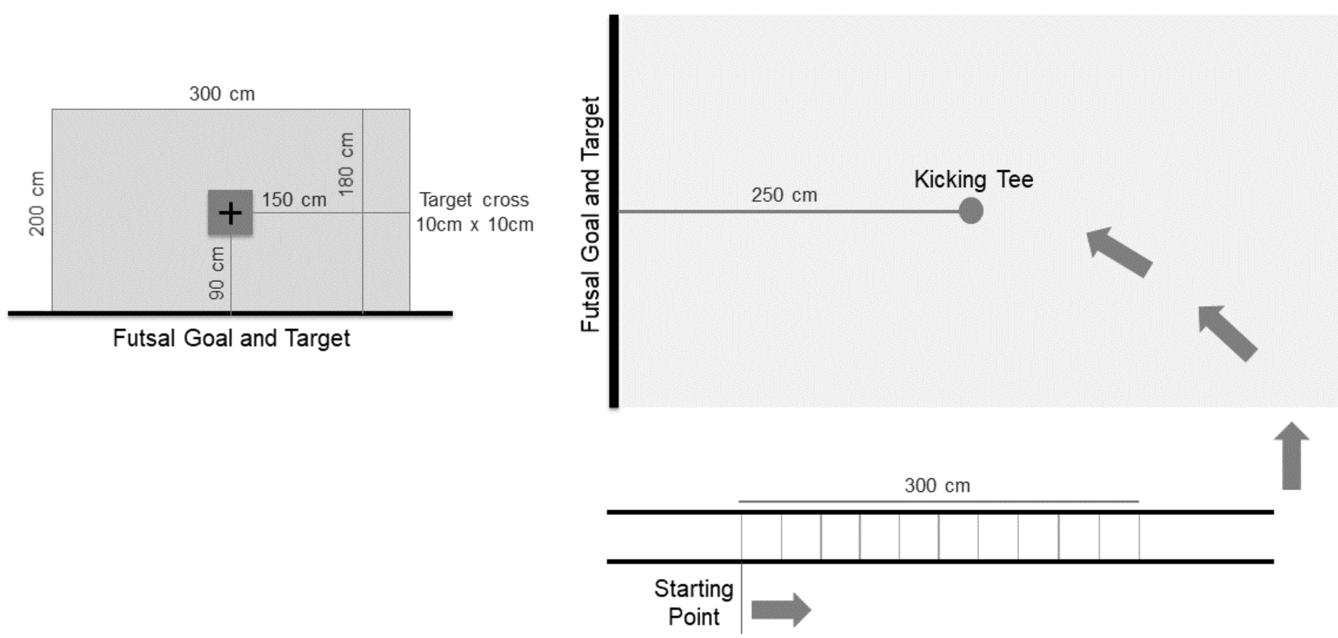

Figure 1: Schematic diagram of the motor task

3. Results

3.1. Self-predicted performance

Multivariate repeated measures ANOVA revealed a significant main effect of colour on self-predicted performance (F(4,31) = 3.11, p = 0.03 η_p^2 = 0.29). Univariate tests showed that the main effect of colour was significant only for self-predicted shooting accuracy (F(2,68) = 5.58, p = 0.006, η_p^2 = 0.14), but not for self-predicted power (F(2,68) = 0.02, p = 0.98, η_p^2 = 0.001). Pairwise comparisons (Figure 2) showed that participants expected themselves to shoot significantly less accurately when they were wearing the red bib (M = 52.96, SD = 16.84) compared to when wearing the blue bib (M = 57.94, SD = 18.70, p = 0.004), or the black bib (M = 57.23, SD = 17.97, p = 0.014). The difference between the blue and black bibs was not significant (p = 0.67). There was no main effect of sex (F(2,33) = 1.83, p = 0.18, η_p^2 = 0.10), and there was no interaction between colour of bib and sex (F(4,31) = 1.13, p = 0.36, η_p^2 = 0.13).

3.2. Actual performance

Multivariate repeated measures ANOVA revealed no main effect of colour on actual performance variables (F(4,31) = 1.43, p = 0.25, η_p^2 = 0.16). There was a main effect of sex (F(2,33) = 10.28, p < 0.001, η_p^2 = 0.38). Tests of between-subjects effects showed that the main effect of sex was significant only for power (F(1,34) = 20.64, p < 0.001, η_p^2 = 0.38) and not for accuracy (F(1,34) = 1.33, p = 0.26, η_p^2 = 0.04). Males displayed greater kicking power than females across all bib colours (all p's < 0.01). The interaction between colour of bib and sex was not significant (F(4,136) = 0.54, p = 0.70, η_p^2 = 0.02). Performance variables are illustrated in Figure 3.

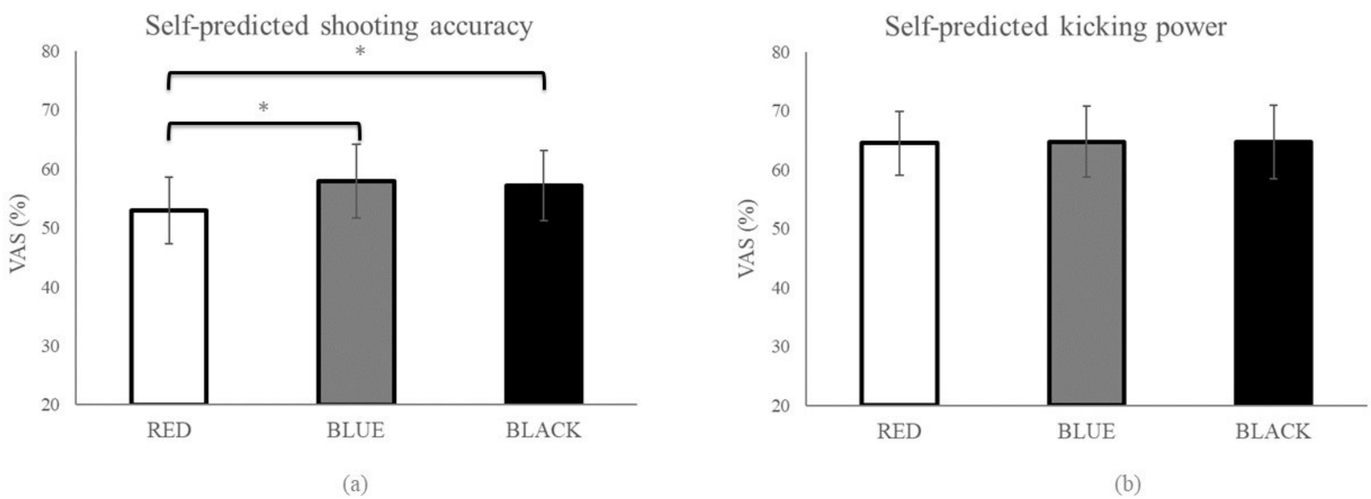

Figure 2: Mean (2SE) of participants' self-predicted performance in (a) shooting accuracy and (b) kicking power; * statistically significant difference

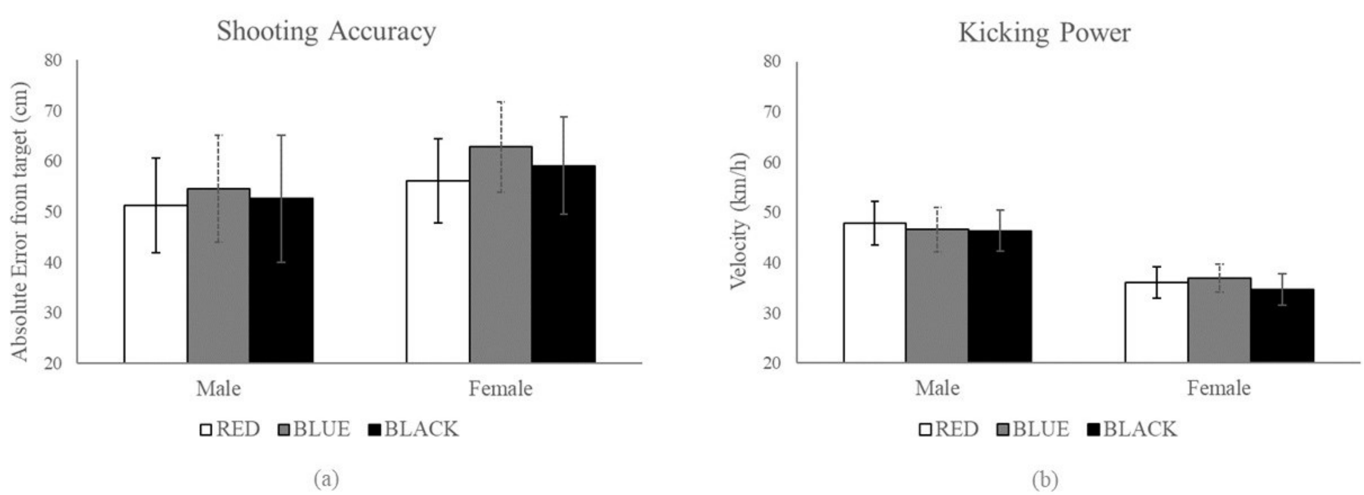

Figure 3: Mean (2SE) of male and female participants' actual performance in (a) shooting accuracy and (b) kicking power

4. Discussion

This study explored the impact of colour on performance of a relatively complex motor task with reasonably controlled context-specific constraints. Based on previous research done in other sporting contexts and colour presentations (i.e., physical environment, opponents' apparel), it was hypothesized that the colour red would have an enhancing effect on participants' self-predicted and actual performance. We found that participants predicted themselves to be less accurate with shooting when they were wearing the red bib compared to the blue and black bibs. However, colour did not have a significant effect on shooting performance.

The current findings appear to contradict the hypothesis regarding self-predicted performance, as the participants predicted themselves to have lower shooting accuracy when wearing the colour red, compared with the colours blue and black. Hill and Barton (2005) claimed that wearing red enhances one's self-perception of dominance and aggressiveness, presumably generating a heightened self-perceived performance. Elliot and Maier (2014), however, argued that factors such as task difficulty and the extent to which an individual's ability could make evaluation threatening could eliminate the positive effect of red. As our participants were novices to football, it is likely that they deemed the football drill task to be difficult and that they considered their ability to be insufficient to win the prize money for the top performers. This probably explains the negative effect of red apparel on participants' self-perceived shooting accuracy.

Our findings suggest that rather than gaining some advantage through enhanced perception of potential success in the primary task, wearing red could have a negative effect. While the findings of this study counter our hypothesis, they nevertheless contribute directional and context-specific evidence, where the effects of colour red on self-predicted performance could be moderated by the task complexity, participants' ability and experience. Whilst we acknowledge that the effect of red on self-predicted performance was found only for shooting accuracy and not for kicking power, this is arguably the more relevant dimension. Participants were instructed to complete a football drill, the goal of which was to kick a ball towards a target accurately. It is therefore likely that the shooting accuracy was the only performance dimension that mattered to the participants.

On the basis that perception and performance are intricately linked, we hypothesized that colour would have an impact on motor performance. On all dimensions, our findings revealed that colour did not influence actual performances in shooting accuracy and kicking power. Apart from archival studies, some experiments had shown that the colour red can promote enhanced performance in motor tasks such as target shooting (Sorokowski & Szmajke 2011), and pinch and hand gripping (Elliot & Aarts 2011). These studies, however, introduced colour manipulation in the form of objects that were presented to participants (i.e., balls, printed materials). In the current study, we specifically tested the effect of colour that participants had on themselves, and the results do not support our hypothesis. This suggests that wearing red apparel does not have an enhancing effect on motor performance, hence no direct advantage might be expected. The task in this study was to shoot at the target accurately; we are unable to rule out the possibility that wearing red might potentially have an effect if the task was focused on the speed of task completion.

We note that the participants were novices, and the lack of practice or training may account for their performances being relatively comparable across the bib colours (i.e., they were still learning the task). Looking at the shooting accuracy data, participants were indeed shooting quite far from the target (see Figure 3). It has been suggested that the effect of red on performance would likely manifest in situations where the task is moderately challenging and extreme situations might weaken or eliminate the effect (Elliot & Maier, 2014). For the novice participants, the football drill task is perhaps greater than a moderate challenge, hence the effect of red was eliminated. Future work could consider having participants with a range of experiences to verify the moderating role of the task challenge on the effect of red (and other colours). Additionally, a manipulation check could be introduced in which participants may rate the level of challenge or difficulty that they experienced with the task. We also consider that the number of trials might have been too few, such that we are unable to rule out a learning effect for the novice participants. Future work could consider a greater number of trials if participants are new to the task. It is also worth noting that the exposure to the colour manipulation was relatively brief (i.e., 30 seconds of focused exposure in front of the mirror), and we cannot rule out the possibility that this was simply not enough to generate an effect on performance. In the current absence of evidence-based recommendation, further work is also needed to verify the optimal time of exposure for sufficient colour manipulation.

We did not find different effects of colour between male and female participants in self-predicted or actual performance. Hill and Barton (2005) who examined the association of colour of apparel with winning in the Olympics found that the apparent advantage of red was found only in male and not in female taekwondo and wrestling athletes. In other studies, males and females have been shown to respond differently to red colour (Elliot & Niesta, 2008), but these tend to be in the contexts of attraction (e.g., Gueguen, 2012; Kayser, Elliot, & Feltman, 2010) or distraction (e.g., Ioan et al., 2007). There has been no prior experimental study that had shown such interaction of red with sex, in relation to motor performance. Whilst we found that males displayed greater kicking power than females, there was no interaction of sex with colour. The difference that we found between males and females is likely due to biological differences in lower limb strength (Miller, MacDougall, Tarnopolsky & Sale, 1993). Our findings suggest that the apparent effect of red on self-predicted motor performance is no different between males and females, and there does not seem to be any difference when it comes to actual performance as well.

The design employed in this study was intended to achieve a reasonable level of control for context-specific constraints. Consequently, there is a trade-off between controlled colour exposure and actual field conditions. It is, therefore, important to consider some design-related limitations when interpreting the evidence. We had mentioned that the wear time and exposure to the apparel colours were relatively short as they were confined to the time required to complete the task trials. In field conditions, athletes would wear the colours for much longer periods of time, and the effects could possibly be different.

To conclude, this study shows that wearing colour red is associated with lower self-predicted performance of shooting accuracy in a football drill. Colour of attire does not directly influence actual shooting accuracy and kicking power. In a relatively complex motor task, the colour that novice performers wear could influence their expectations, but not their actual performance.

Conflict of Interest

The authors declare no conflict of interest.

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Music can induce positive affect before football training, but is it maintained throughout training?

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ABSTRACT

In a sport setting, affective states interact with other constraints to influence athlete skill acquisition and performance. The importance of affect in skill acquisition is given weight through the underpinnings of representative and affective learning design frameworks. However, there is currently a lack of understanding how the affective states of athletes change throughout training activities. This study aimed to understand how association football players' affective states changed throughout training. Prior to four training sessions, positive and negative music was used as a treatment to induce affective states in 12 competitive-elite youth footballers (M = 17.36, SD = 1.11 years). During training, players participated in a series of six small-sided games, and their affective states (valence and arousal) were monitored prior to each game using the Affect Grid. RM-MANOVA revealed that the music treatment was able to effectively influence affective states. Further, positive affect remained high for some time throughout training, whereas affective states returned to pre-treatment levels at the beginning of training when athletes listened to negative music prior to the training session. Musical interventions may offer a suitable solution for practitioners to implement affective learning designs into their training.

1. Introduction

Positive affective states,[1] conceptualised as the subjective experience of pleasure and arousal (Russell & Barrett, 1999), have been shown to have a supportive influence on many subcomponents of sport performance and have become a captivating area of research (Fredrickson, 2013; McCarthy, 2011; Wang et al., 2011; Woodman et al., 2009). Given the influence of affective states on motor learning and skill acquisition (Festini, Preston, Reuter-Lorenz, & Seidler, 2016; Headrick, Renshaw, Davids, Pinder, & Araújo, 2015; Runswick, Roca, Williams, Bezodis, & North, 2018), it has been suggested that practitioners should endeavour to manipulate affective states prior to and during training tasks (Beatty & Janelle, 2019). Indeed, it is common that practitioners and athletes will make use of strategies to optimise affective states prior to competition, for example by listening to music (Karageorghis, Bigliassi, Tayara, Priest, & Bird, 2018). Consequently, there is a need to understand the influence of these interventions on affective states and changes in these states throughout competition. Given the reported impact of positive affect on performance and learning, it is necessary to understand how affective states fluctuate throughout training and competition, as attempts to induce positive affect prior to competition may be irrelevant if the affective state is not maintained throughout play. By understanding these *dynamics of affect*, practitioners and researchers alike may have more confidence in the expected performance and learning advantages of positive affect during activities with longer duration and where athletes' affective states cannot be monitored often, such as association football. Therefore, the current study aimed to provide further understanding of the potential role of affective states in

[1] For the purpose of the current research, positive affective states refer to the subjective experience of the affective state as opposed to the function of the affective state.

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association football by providing an initial understanding of the dynamics of positive and negative affect throughout play.

Positive affective states have been linked to performance gains in basketball (Uphill, Groom, & Jones, 2014), softball (Vast, Young, & Thomas, 2010), table tennis (Martinent & Ferrand, 2009), cricket (Totterdell, 2000), cycling (Lane & Terry, 1998), and running (Lane, Davis, & Devonport, 2011). Further, positive affective states have been shown to influence subcomponents of sport performance in a range of ways (McCarthy, 2011). For example, positive affect has been found to influence perception, attention, memory, decision-making, and judgment (Forgas, 1995, 2002; Isen, 2000; Vast et al., 2010). In addition, positive affective states have been suggested to foster more relaxed and expansive bodily movement (Giraud, Focone, Isableu, Martin, & Demulier, 2016; Gross, Crane, & Fredrickson, 2012), as well as more automatic movement on well-learned tasks (Vast et al., 2010). Of specific relevance to association football, these performance subcomponents have been related to successful match-play. For example, attention and decision-making (Araújo, Hristovski, Seifert, Carvalho, & Davids, 2017; Hüttermann, Ford, Williams, Varga, & Smeeton, 2019), visual perception (McGuckian, Cole, Chalkley, Jordet, & Pepping, 2019, 2020; McGuckian, Cole, Jordet, Chalkley, & Pepping, 2018), and memory (Furley & Wood, 2016) are all widely recognised as important subcomponents of football match-play that can be reliably linked to positive football performance outcomes.

From a team perspective, it appears that positive affective states may provide other benefits to performance. The experience of positive affect as a team becomes an important aspect of the team environment, as positive affective states may influence attachment, affiliation, resilience, cohesion, cooperation, and interpersonal trust (Morgan, Fletcher, & Sarkar, 2015; Oatley, Keltner, & Jenkins, 2006; Pepping & Timmermans, 2012). Creating an environment within a team where the athletes work toward a common goal and feel a connection to one another is an important aspect of performance, and this is enhanced by experiences of positive affect (Pepping & Timmermans, 2012).

The broaden-and-build theory of positive emotions posits that, compared to negative and neutral states, positive affective states widen the scope of one's thoughts and actions, fostering more flexible, creative, forward-looking, and efficient thought and action patterns (Fredrickson, 2013). In addition, the broadening effects of positive affect are suggested to spur the development of resources and encourage positive growth (Fredrickson, 2013). These broadening effects appear particularly relevant from a motor learning and skill acquisition perspective, as inducing positive affective states prior to and during training may support the development of motor skill through greater exploration of movements and adaptability (Komar, Potdevin, Chollet, & Seifert, 2019; Orth, Davids, & Seifert, 2017).

Efforts to induce positive affective states prior to and during sport competition are common (Terry, Karageorghis, Curran, Martin, & Parsons-Smith, 2020). Given the relationship between music and positive affective states (Croom, 2015), music is often used in sport and exercise domains (Bishop, Karageorghis, & Loizou, 2007; Karageorghis, Terry, Lane, Bishop, & Priest, 2012; Laukka & Quick, 2013). While many sports do not allow the use of music during competition, it is very common for athletes to listen to music before competition and during warm-ups (Bishop et al., 2007; Karageorghis et al., 2012). The use of music in sport, and the notion that music can have a beneficial impact on affective states and performance before and during exercise participation, is well supported by research (Bishop et al., 2007; Boutcher & Trenske, 1990; Karageorghis et al., 2012; Lane et al., 2011; Terry et al., 2020). Music has been used to induce positive affective states in many applied and research domains, and it has been shown that careful selection of music can reliably induce positive affective states (Bishop, 2010; Bishop, Karageorghis, & Kinrade, 2009; Chen, Yuan, Huang, Chen, & Li, 2008; Crust, 2008; Terry et al., 2020). For music to have a maximal impact on affective states, it has been suggested that music should be selected methodically and that factors such as extra-musical associations, acoustical properties (such as tempo and rhythm), identification with lyrics, and familiarity of the music should be considered (Bishop, 2010; Karageorghis et al., 2012). In association football, music has been described to be used as a stimulant and regulator of affect prior to performance (Karageorghis et al., 2018). It was shown that music was able to elicit a range of psychological and group-level psychological responses among academy soccer players and that music could be employed as a useful performance-enhancing tool.

For the purposes of the current study, we follow an ecological approach (Gibson, 1979; Reed, 1996) and propose that music, as part of the sonic environment, can be an integral part of the athlete-environment system. As such, music has been shown to influence movement, synchronisation and interpretation of future events. Relevant to the current study, music can influence an athlete's action-tendencies (action readiness) and affective states (Reybrouck, 2015; Windsor & de Bézenac, 2012) and thereby perception and action in relation to the available affordances – the field of relevant affordances (Rietveld & Kiverstein, 2014). From this approach, emotions, or affective states, should be understood as means of establishing relationships with the environment (see Withagen, 2018; Withagen, de Poel, Araújo, & Pepping, 2012). A recognition of affective states in perception and action in relation to affordances in practice tasks also forms the basis of Affective Learning Design (Headrick et al., 2015; Renshaw, Headrick, & Davids, 2014) and more broadly Representative Learning Design (Connor, Farrow, & Renshaw, 2018; Krause, Farrow, Buszard, Pinder, & Reid, 2019; Pinder, Davids, Renshaw, & Araújo, 2011; Robertson, Spencer, Back, & Farrow, 2018). In short, these frameworks posit that practice situations should simulate the important aspects of the performance environment in order to best represent the affordances available in the performance environment and thereby facilitate learning and performance. Despite emotional aspects of sport contributing to performance, this area of practice design has been largely overlooked in research (Headrick et al., 2015), indicating a need to gain further understanding of affective states within motor learning environments. In doing so, an understanding of changes to both positive and negative affective states before and during training is necessary to help inform the implementation of Affective Learning Designs.

In many sports, the dynamics of affect (i.e., how affective states change over time) are currently not well understood. Lane et al. (2011) found that the affective state of runners did not change during a distance run, however affective valence appeared to decline when running intensity exceeded ventilatory threshold (Benjamin, Rowlands, & Parfitt, 2012; Hall, Ekkekakis, & Petruzzello, 2002). In contrast, Martinent and Ferrand (2009) reported rapidly varying emotions during competitive table tennis matches. Semi-structured interviews with athletes showed that athletes from a number of sports experienced varying affective states before, during, and after competition (Uphill & Jones, 2007). The limited research into affective states during *team* sport play shows similar results. Uphill et al. (2014) found that basketball players experienced a wide range of emotions throughout competition, however only a small percentage of playing time was described as emotional (9%). Runners (relatively stable affect) and basketballers (rapidly changing affect) compete under vastly different task constraints, therefore, these differing results across types of sport may be due to the differing timescales, intensities and demands of competition. The lack of current understanding in association football demonstrates the need for further research into the dynamics of affect throughout team-play activity.

To inform the implementation of Representative Learning Designs, Affective Learning Designs and the use of music to influence affective states, the aim of the current study was to describe the influence of pre-training music use on affective states, and the dynamics of musically induced affective states throughout football training. It was expected that listening to music before training would effectively influence affective states. It was expected that affective states would fluctuate throughout training, however investigation of these changes was considered exploratory and specific hypotheses relating to these changes were not made.

2. Methods

2.1. Participants

Twelve male youth football players aged between 16 and 19 years (M = 17.36, SD = 1.11) were conveniently recruited to participate in the study. Participants were all members of the same youth team competing in the Australian National Youth League. Players were eligible for participation in the study provided they were not injured and were available to train on data collection days. A typical training week for participants included 3-4 training sessions of approximately 70-minutes, plus a 90-minute match each weekend. All participants were deemed fit to train by the team physiotherapist.

The study was approved by the Human Research Ethics Committee (HREC) of the Australian Catholic University prior to the commencement of the study. The participants (and their legal guardians) were informed of the research procedures, risks, and benefits both verbally and via a written information letter. Prior to the beginning of the study, consent was obtained from participants over 18 years. For participants under 18 years, assent was obtained along with consent from their legal guardians.

2.2. Research Design

In this repeated-measures experimental study, two music conditions were implemented to explore the influence on affective state. Affective states were monitored eight times over the course of training sessions, for four separate training sessions. As a result, a 2 x 8 factorial design was used, with affective valence and arousal as the dependent variables.

2.3. Measures

Brunel Music Rating Inventory-2. The Brunel Music Rating Inventory-2 (BMRI-2; Karageorghis, Priest, Terry, Chatzisarantis, & Lane, 2006) was used as a methodological check to ensure the motivational quality of music selected by the participants and researcher. The BMRI-2 is considered a valid and internally consistent tool for music selection with Chronbach's alpha values ranging between 0.86 and 0.88 in samples of young men (Karageorghis et al., 2006), and has been used often in research with young adults (Barwood, Weston, Thelwell, & Page, 2009; Hutchinson & Sherman, 2014; Terry, Karageorghis, Saha, & D'Auria, 2012). Consisting of six items, the BMRI-2 assesses the motivational quality of six structural components of music using a 7-point Likert scale, which when added together give an overall score for the motivational quality of the song. A higher score indicates the musical piece has higher motivational quality, with a maximum score of 42. Songs rated between 18 and 30 on the BMRI-2 are classified as oudeterous, neither motivating nor demotivating (Terry et al., 2012). The BMRI-2 has been used a number of times in research of a similar nature (Lane et al., 2011; Simpson & Karageorghis, 2006; Terry et al., 2012). The instructions for each item on the BMRI-2 were modified from the original (… motivate me *during* exercise) to suit the context of pre-training music listening (… motivate me *before* exercise) (Karageorghis et al., 2006).

Affect Grid. To assess the *dynamics* of affect, affect should be measured often *throughout* the bout of exercise (Ekkekakis & Petruzzello, 2000; Rose & Parfitt, 2012). A modified version of the Affect Grid (Russell, Weiss, & Mendelsohn, 1989) was utilised to assess the affective state of participants throughout the study. The original grid was modified for the study to enhance the ease of verbal reporting; the participants could visually select the appropriate cell and communicate the two numbers in the cell very quickly. The first number represented valance via the displeasure-pleasure dimension while the second number represented arousal via the sleepiness-arousal dimension. Both dimensions use a numerical scale from 1-9. The simple and brief response required allowed the Affect Grid to be used on multiple occasions with brief periods between each response (Russell et al., 1989), while ensuring the participants do not tire from the scale. Participants were familiarised with the Affect Grid prior to data collection. The scale has been shown to have adequate reliability (Russell et al., 1989) and moderate validity (Killgore, 1998), and has been used in previous research concerning affect in exercise domains (Bishop et al., 2009; Golden, Tenenbaum, & Kamata, 2004; Hardy, Hall, & Alexander, 2001; Rikberg, Raudsepp, & Kais, 2011).

2.4. Procedure

It was assumed that highly motivating music (according to BMRI-2 ratings) would result in positive affective states, while less motivating music would result in negative affective states. Two types of music playlist were created prior to the first data collection day; a positive playlist intended to induce positive affect before training, and a negative playlist intended to induce negative affect before training. To avoid arbitrary selection of music and to maximise the effectiveness of the playlist, each participant's positive playlist consisted of individually selected songs (Bishop, 2010; Karageorghis & Terry, 1997; Karageorghis et al., 2012). Further, to ensure music selection was perceived to be meaningful and valuable, participants were asked to select five songs that they felt would ideally prepare them prior to a match. The songs selected by participants were predominantly high-tempo electronic and dance songs. As the participants knew they would be required to listen to the songs prior to training, we presumed it unlikely that the participants would willingly select songs that effectively induce negative affective states. Therefore, songs for the negative playlist were preselected by the researchers and were the same for all participants (Table 1). These songs were low-tempo and had broadly sad lyrics in an attempt to induce a negative affective state.

Table 1: Songs preselected by the researchers for the negative music playlist

Title	Artist	Mean (SD) BMRI-2 rating
Yesterday	The Beatles	11.58 (2.61)
Mad World	Gary Jules	10.67 (3.58)
Everybody Hurts	R.E.M	13.33 (6.37)
Tears in Heaven	Eric Clapton	9.25 (3.05)
Wasting My Young Years*	London Grammar	18.33 (9.26)

* Removed from negative playlist

Prior to the first data collection day, participants assessed the motivational quality of each song on their own positive playlist and the negative playlist using the BMRI-2 (Karageorghis et al., 2006). One song was rated within the oudeterous range and was therefore removed from the negative playlist. The resulting negative playlist to be used on data collection days included the remaining four songs.

Data collection was completed over four days during the National Youth League season in Australia (Figure 1). On each data collection day, participants were split evenly into either a positive affect or negative affect group. In order to induce positive and negative affect, the positive affect group was assigned a positive playlist of music (i.e., their own selected playlist), while the negative affect group was assigned the negative playlist of music. Over the four data collection days, participants were alternatively assigned to each affect group twice each. This assignment ensured the positive and negative affect groups had six participants each day, and each participant was in the positive affect group twice and the negative affect group twice.

Participants arrived at the training facility approximately 60 minutes prior to the beginning of training, at which point they gave a rating of their affective state (time point 1, check-in). At 15 mins prior to training, participants were given an mp3 device loaded with either their positive playlist or the negative playlist. If the participants had their own personal headphones, they were allowed to use them, otherwise they were given headphones to use. To cater for individual preferences, participants were permitted to self-select the volume of their music. Music exposure lasted for 10 mins. At 5 mins prior to training, participants stopped listening to music and verbally gave a second rating of their affective state (time point 2, post-music). Participants began training with a standard warm-up conducted by the coaching staff. The warm-up lasted 15 mins and was completed as a team. Coaching staff, who were blinded to music exposure, then split the participants into random teams in preparation for a series of small-sided games (SSG), each lasting 2 mins. SSG's of this nature were a commonly used activity for the participants. Prior to each of the six SSG, participants verbally communicated their affective state (time point 3, 4, 5, 6, 7, and 8).

2.5. Statistical Analysis

As a methodological check for the predicted effectiveness of the positive and negative playlists, a paired samples t-test with Bonferroni correction was performed to compare the BMRI-2 ratings of participants' own positive playlists and the negative playlist.

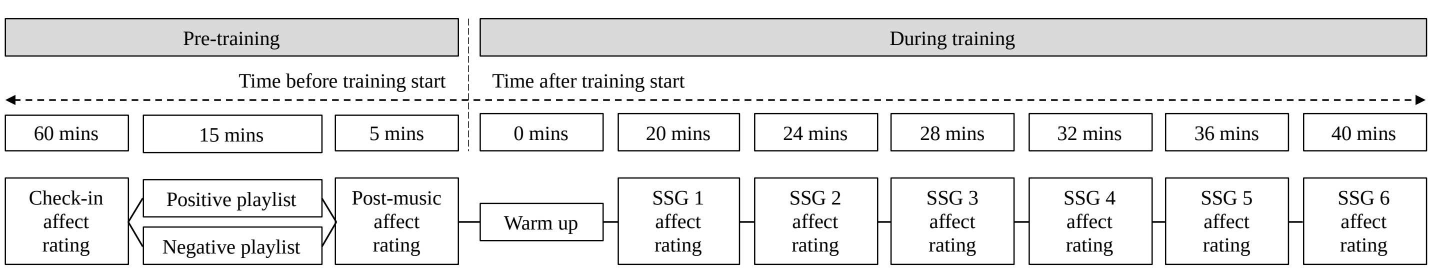

Figure 1: Experimental design and timeline for each of the four data collection days

Repeated-measures multivariate analysis of variance (MANOVA) was performed to assess the effect of type of music and moment in time on ratings of valance and arousal on the Affect Grid. The independent variables were type of music (two levels, positive and negative) and moment in time (8 levels; check-in, post-music exposure, and before SSG 1, 2, 3, 4, 5, and 6), and the dependent variables were valance and arousal as measured by the scores on the Affect Grid. When Mauchly's test indicated the assumption of sphericity had been violated, Greenhouse-Geisser correction was applied to the degrees of freedom. To assess affect differences over time from baseline, planned simple contrasts were performed separately for the positive and negative music groups with valence and arousal scores at check-in as the reference category. Alpha was set at 0.05 throughout.

3. Results

3.1. Affect Responses to Music

The mean (*SD*) BMRI-2 rating for the negative playlist was 11.21 (2.82) and 36.35 (2.66) for the individualised positive playlists. Paired samples t-test revealed a significant difference between the BMRI-2 ratings of the positive and negative playlists, $t(11) = 19.86$, $p < .001$, indicating that the positive playlist was rated significantly higher than the negative playlist.

Repeated measures MANOVA revealed a simple main effect of music type on valance ($F(1,11) = 6.967$, $p = .023$, $\eta_p^2 = .388$), and arousal ($F(1,11) = 4.867$, $p = .050$, $\eta_p^2 = .307$). Results show that music was able to effectively alter the valance and arousal states of youth football players prior to their training (Table 2).

3.2. Dynamics of Affect Throughout Play

Valence ratings over time for the positive and negative music conditions are shown in Figure 2. Arousal ratings over time for the positive and negative music conditions are shown in Figure 3. Repeated measures MANOVA showed no simple main effect of time on valence scores ($F(3.28, 36.09) = 1.173$, $p = .335$), however there was a simple main effect of time on arousal scores ($F(3.38, 37.21) = 2.946$, $p = .040$, $\eta_p^2 = .211$). Repeated measures ANOVA showed an interaction effect of type of music x time on valence scores ($F(2.66, 29.33) = 3.799$, $p = .024$, $\eta_p^2 = .257$) and an interaction effect of type of music x time on arousal scores ($F(3.53, 38.78) = 4.630$, $p = .005$, $\eta_p^2 = .296$). Planned simple contrasts of valence and arousal over time with time at check-in as the reference category for the positive and negative music type are displayed in Table 3.

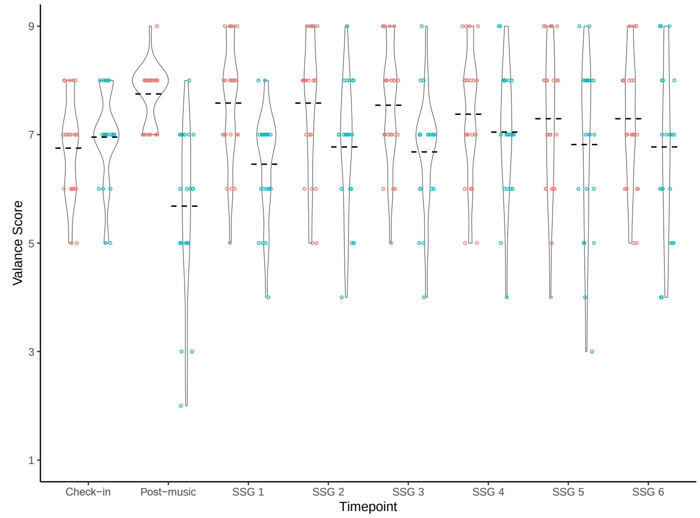

Figure 2: Violin plots showing valence scores over time for the positive and negative music conditions. Points indicate individual observations, dashed lines indicate group means.

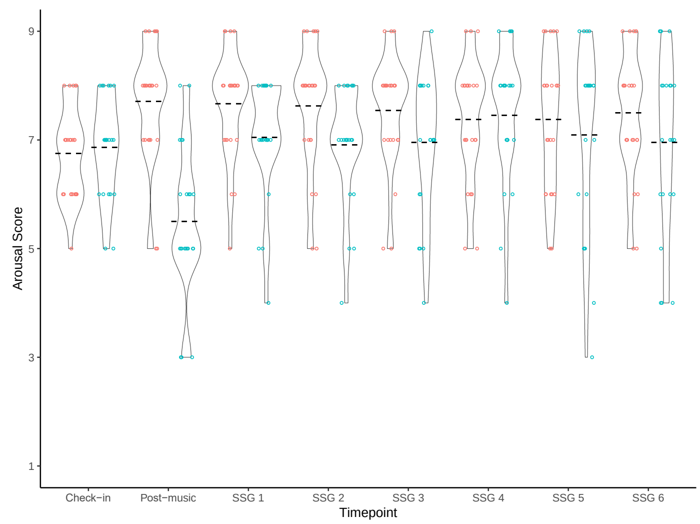

Figure 3: Violin plots showing arousal scores over time for the positive and negative music conditions. Points indicate individual observations, dashed lines indicate group means.

Table 2: Mean (SD) valence and arousal scores pre- and post-music for the positive and negative music conditions.

	Mean (SD) valence		Mean (SD) arousal	
	Pre	Post	Pre	Post
Positive music	6.75 (0.81)	7.71 (0.40)	6.67 (0.81)	7.63 (1.07)
Negative music	6.96 (0.86)	5.50 (1.64)	6.88 (0.86)	5.33 (1.35)

Table 3. Planned simple contrasts of valence and arousal over time with time at check-in as reference category for the positive and negative music conditions.

	Positive Playlist				Negative Playlist			
	Valance		Arousal		Valance		Arousal	
Time point	*F*	η_p^2	*F*	η_p^2	*F*	η_p^2	*F*	η_p^2
Post-music vs. Check-in	**16.769***	**.604**	**8.830***	**.445**	15.834*	.590	27.939**	.718
SSG 1 vs. Check-in	**6.102***	**.357**	**8.250***	**.429**	3.541	.244	0.000	.000
SSG 2 vs. Check-in	**5.754***	**.343**	**5.711***	**.342**	1.035	.086	**0.137**	**.012**
SSG 3 vs. Check-in	**4.666**	**.298**	**5.848***	**.347**	3.000	.214	**0.147**	**.013**
SSG 4 vs. Check-in	**3.143**	**.222**	**2.983**	**.213**	**0.187**	**.014**	**1.220**	**.100**
SSG 5 vs. Check-in	**1.709**	**.134**	**2.936**	**.211**	1.692	.133	**0.155**	**.014**
SSG 6 vs. Check-in	**2.462**	**.183**	**5.189***	**.321**	1.960	.151	**0.542**	**.047**

Note: Bold text indicates mean value is higher than check-in value. * $p < 0.05$, ** $p < 0.01$.

4. Discussion

To inform the implementation of Affective Learning Designs and the use of music to influence affective states, the aim of the current study was to describe the dynamics of affective states throughout football training. Music was used as a treatment to induce positive and negative affective states prior to training, and affective states were monitored numerous times throughout training. Results indicated that positive affect could reliably be induced with self-selected positive music, however, negative music resulted in neutral affective states. Positive affective states were partially maintained during training, whereas neutral affective states returned to pre-music treatment levels shortly after the training had started. Whilst this was an exploratory study and no specific hypotheses were developed, our expectation that listening to music before training would effectively influence affective states and that affective states would fluctuate throughout training, were partially confirmed.

The change in affective states following music treatment further supports the use of music as a means of inducing affective states before training in association football. These results fall in line with similar research regarding affect responses to music (Bishop et al., 2009; Karageorghis et al., 2018; Lane et al., 2011; Terry et al., 2020), while also expanding on their findings. The present study had participants choose their own selection of positive music, which may have accounted for the higher affect scores compared to Lane et al. (2011). When selecting music, it has been suggested athletes make extra-musical associations - associations between certain songs and significant people, places or events - which maximises the effectiveness of the selected songs (Bishop, 2010; Bishop et al., 2007). By self-selecting positive songs, it is likely the participants made extra-musical associations with the songs, which may have accounted for the positive affect following music exposure. Given the frequency that athletes use music prior to competition, this finding has important implications for applied practitioners. Self-selecting music is a relatively straightforward task for athletes competing in individual sports, however, this may present a challenge in team sport settings. It is common that teams will listen to the same music through a single set of speakers, which may limit the value of this musical intervention if some athletes do not have strong extra-musical associations with the music that is used. In this case, it may be more beneficial for athletes to listen to self-selected music through personal music devices in order to maximise the benefits associated with musical interventions.

The negative music was unable to induce negative affective states. Rather, the findings demonstrate that neutral (or less positive) affective states can be induced through the use of music. Although it may seem counter-intuitive to try to induce negative affect in a sport setting, this idea may warrant further attention in an affective learning design domain (Headrick et al., 2015). Although a positive affective state may be ideal in a competitive environment, it is inevitable that athletes will experience negative affective states at some point during competition, and that these states will interact with other constraints to influence the athlete's performance capabilities. Therefore, the ability to induce negative affective states and include these states as an element of a representative learning environment may provide some value. When further using music to induce negative emotions to investigate their role in affective learning designs, it would be important to ascertain whether the induced affect is representative of the negative affect experienced during competition.

Results indicated that neutral affective states were apparent immediately following the music intervention but were not maintained throughout training, however the exact reason for this is unclear as the present study did not include a control condition. It may be that affective states became more positive in anticipation of training starting, either through self-regulation strategies (e.g., self-talk, Hardy et al., 2001) or the enjoyment of participating in the team warm-up. Further, since the negative music was not self-selected, these songs may have lacked the meaning ("aboutness") or association compared to the music used to illicit positive affective states. Future research in this area should further investigate the factors influencing the endurance of affect and the importance of the ability to self-select music, as the findings may provide valuable insight into the use of various affective states in learning environments.

A range of individual and team performance factors, such as involvement, interaction with teammates/coaches/opponents, other than the music intervention, are likely to have influenced the affective state of players in the SSGs. Further, whilst the players trained in teams, in the current study we have focussed on presenting individual participant affective states. That is, on the basis of the presented data, we cannot draw conclusions in relation to the effects of the individual affective states on the team or on interpersonal processes (e.g., interpersonal dynamics, team performance) (Beatty & Janelle, 2019). Nevertheless, the findings give an initial understanding of the dynamics of affect throughout play in a team sport setting. This was the first study of its kind in team sport, which is important considering the greater range of interacting constraints that are present in team sport compared to the individual sports that this type of research typically investigates (Benjamin et al., 2012; Hall et al., 2002; Lane et al., 2011). Athletes' positive affective states remained elevated for some time; however, this effect was not sustained for the entire training session. A possible explanation for this may come from the intensity of play as a training session progresses. It has been shown that, as exercise intensity rises above an athletes preferred level of intensity, affect, typically, decreases (Lind, Ekkekakis, & Vazou, 2008; Parfitt & Hughes, 2009). Benjamin et al. (2012) found that adolescents' affective states remained fairly constant for moderate intensity exercise, however when exercise reached higher intensity, affective states showed a significant decline. Small sided games, as used in the current research, are typically high intensity (Hill-Haas, Dawson, Impellizzeri, & Coutts, 2011), so as training progressed it is likely the athletes' affective states declined in line with the perceived intensity of training. Further, participants were asked to select and rate music in preparation for a match, whereas data were collected prior to and during training. It is unclear how the difference in the intended context may have influenced the music selection and rating, and consequent impact of music of affective states.

The present study aimed to understand football players' affective responses to positive and negative music treatment before training, and the dynamics of football players' affective states throughout team play. The results supported the use of music as a means of inducing affective states, particularly in the case of positive affective states, as they were maintained for a longer period throughout training. Researchers should seek to expand on the present study to further understand the potential benefits of using musically induced affective states in a training environment.

It is recommended that practitioners consider the impact that music may be having on athletes' affective states prior to training and games (Karageorghis et al., 2018; Terry et al., 2020). To ensure the maximum impact of music use, it is recommended that music is self-selected and a validated measure such as the BMRI-2 (Karageorghis, 2016; Karageorghis et al., 2006) is used to verify the potential value of the selected music. Given the prevalence of music use prior to games, practitioners may wish to make systematic use of music prior to training to enhance the representativeness of activities (Krause et al., 2019; Pinder et al., 2011) or to implement affective learning designs (Headrick et al., 2015) into their training. It is recommended that affective states are monitored frequently to ensure that the expected states are achieved and maintained.

Conflict of Interest

The authors declare no conflict of interests.

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A normalized brake work algorithm designed to output a single metric to predict non-propulsive mountain bike performance

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ABSTRACT

The use of a brake power meter is invaluable for describing descending performance in cycling. However, the interaction between variables such as brake work, brake time and brake power can be intricate, which might be a barrier to the utility of the brake power meter as a training tool. The aim of this study was to determine if brake power can be normalized to create a single-metric output that can capture braking performance during descents. Nine nationally competitive mountain bikers completed three trials each at race pace on a mountain bike descent using a bicycle equipped with a brake power meter. Brake power was normalized instantaneously by dividing it by the kinetic energy of the bicycle-rider system and was integrated to calculate normalized brake work (unitless). Normalized brake work (26.3 ± 15.3) was more strongly correlated (r^2 = 0.929; p < 0.001) with descending performance time (130.8 ± 20.1 s) than relative brake work (676.0 ± 152.3 J/kg; r^2 = 0.477; p < 0.001), brake time (62.3 ± 21.1; r^2 = 0.729; p < 0.001) or relative brake power (11.4 ± 2.2 W/kg; r^2 = 0.429; p < 0.001). On the descent used in this study, normalized brake work was the strongest indicator of descending performance based on braking. It is recommended that this metric be used to quickly assess brake use and provide feedback to cyclists.

1. Introduction

Performance indices and predictive models in cycling sports have remained popular throughout the literature as these provide capacity for guided analyses and training interventions. To inform training, however, these indices must be valid, i.e., they must accurately separate good and poor performance (Buekers & Magill, 1995; Buekers et al., 1994; Ford et al., 2007; Ryan et al., 2002). In particular, novice learners are especially dependent on receiving valid feedback to perform correctly (Buekers et al., 1994; Ford et al., 2007). Thus, it is critical that the performance indices used to guide training are valid.

Historically, investigative models in cycling sports have focused almost exclusively on measurements of propulsive power output and propulsive work collected from on-the-bike power meters in the drivetrain (e.g., Hurst & Atkins, 2006; Macdermid et al., 2014; Miller et al., 2015; Steiner et al., 2016). Data gathered from these power meters have been able to predict the variance in cycling performance. For example, relative rates of propulsive work have a strong negative correlation with the time to complete a climb. For the practitioner and athlete, this means that to improve performance on uphill sections, competitors must aim to increase rates of relative propulsive power (W/kg). Accordingly, the intent of documented training interventions has aimed to increase relative propulsive power.

Propulsion remains an important factor for mountain bike (MTB) performance, and predictive models based on relative power output have proven useful for cross-country racing (Gregory et al., 2007; Prins et al., 2016; Vaitkevičiūtė & Milašius, 2012). However, more recent evidence has highlighted the importance of multi-dimensional performance models based on the highly variable and technical terrain ridden (Chidley et al., 2014; Miller et al., 2019; Novak et al., 2018). Indeed, while MTB ascending performance is strongly linked with relative propulsive power output, descending performance is instead linked to "skill" and not propulsive power at all. As such, a brake power meter was developed to analyze the use of brakes when mountain biking (Miller, Fink, Macdermid, Perry, & Stannard, 2018; Miller et al.

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2019). This new technology proved useful for describing non-propulsive MTB descending/turning and was also employed in conjunction with propulsive power to enhance predictive models in MTB time-trial simulations on varying terrain (Miller et al., 2019). Differences in both braking behavior and performance (i.e., time) between experienced and inexperienced riders were seen in a study of a single turn (Miller, Fink, Macdermid, Allen, & Stannard, 2018), raising the possibility that the inexperienced riders could improve performance by adopting braking patterns more like the experienced riders. There is, however, a need to extend the use of the brake power meter from a single turn, in highly controlled conditions, to a more ecologically valid situation, i.e. a technical descent with turns of different radii and with differences in the approach speed to the turn.

To date, this new brake power meter technology has focused on utilizing the same kinds of variables collected from propulsive power meters – such as power and work – due to their relative relevance, non-complexity and prevalence of use (Miller et al., 2017; Miller, Fink, Macdermid, Perry, & Stannard, 2018; Miller et al., 2019). The measurement of brake work and power is similar to the measurement of propulsive power and work; however, the magnitude of braking necessary to slow riders depends on a number of variables, which complicates the interaction between the brake work and brake power performed and how these affect the speed of the bike. These variables were significantly correlated with performance (i.e., time), but neither variable explained a high percentage of the variance in performance time ($r^2 < .500$, less than the correlation for the time spent braking) (Miller et al., 2019), which may be a barrier to the effectiveness of brake training interventions and descending performance explanation when using a brake power meter.

To highlight some of the complexities of brake power meter data analysis, simple energy equations can be utilized to compare braking data and effects on performance given the law of conservation of energy. At the same time, these same equations may also help to reduce brake power meter data to more usable and comparable metrics. A brief sequence of the braking variables collected and the physical comparisons made are outlined below.

Brake power (W) is calculated as the product of brake torque and the velocity of the bike (Eq. 1):

$$PB = \omega_f (\tau_f + \tau_r)$$

where PB is brake power, ω_f is the angular velocity of the front wheel, and τ_f and τ_r are the brake torque at the front and rear wheels, respectively (Miller et al., 2019).

Brake work (WB, in J) is calculated by integrating the product of front and rear brake power (Eq. 2):

$$WB = \int_0^t (PBf + PBr)dt$$

The brake work completed by a rider slowing down on flat ground is equal to the change in kinetic energy when accounting for drag and rolling resistance (Eq. 3):

$$WB + E_{rr} + E_d = \Delta E_K$$

where, E_{rr} is rolling resistance, E_d is energy lost to aerodynamic drag, and ΔE_K is the change in kinetic energy as explained previously (Miller et al., 2017).

The change in kinetic energy of the bicycle-rider system can be explained given (Eq. 4):

$$\Delta E_K = \left[\left(\frac{1}{2}mv_2^2\right) - \left(\frac{1}{2}mv_1^2\right)\right] + \left[\left(\frac{1}{2}\mathrm{I}\omega_2^2\right) - \left(\frac{1}{2}\mathrm{I}\omega_1^2\right)\right]$$

where m is the combined mass of the bike and the rider wearing cycling gear, v is the velocity, I is the moment of inertia, and ω is the angular velocity of the front wheel.

The instantaneous kinetic energy can therefore be calculated as (Eq. 5):

$$E_K = \left(\frac{1}{2}mv^2\right) + \left(\frac{1}{2}\mathrm{I}\omega^2\right)$$

where v and ω are instantaneous velocity and angular velocity, respectively.

In Eq. 5, m and v are important to note. Assuming two riders of different mass, the kinetic energy at any given time is not equal, and thus the brake work required to slow these two masses will not be equal. More importantly, two riders of the same mass but travelling at different velocities will have different kinetic energy because the kinetic energy of each rider is proportional to velocity squared. For example, a rider traveling twice as fast will require four times the brake work to come to a complete stop. Indeed, with differences in the amount of brake work required, the brake power recorded will be different in these cases—even with the same time spent braking. Although we understand that it is important to complete brake work across a very short brake time to minimize the time spent traveling slowly – and that this leads to a very high brake power – it is difficult to make comparisons between individuals even when accounting for mass. Accordingly, it is understandable why traditional measurements of brake work or average brake power have a relatively weak relationship with performance time across a given distance. This potential barrier to the understanding and comparison of the data must be overcome for brake power meter measurements to have utility for training.

Given the complexities in analyzing brake data, it is sensible to develop an algorithm that can calculate the amount of braking done by the rider in relation to both the total mass and the velocity of the bicycle-rider system. One way to do this could be to divide the instantaneous brake power by the kinetic energy of the bicycle-rider system, resulting in a variable with units of (1/s). This normalization of brake power effectively adjusts the braking power based on both mass and velocity. Then, normalized brake power can be integrated to find normalized brake work, which is a unitless measure. Since MTB descending performance is likely linked to braking and cannot be predicted using propulsive models, a normalized brake work model would help to describe and analyze these performances.

To provide better feedback to cyclists, the aim of this study is to determine what variables correlate most strongly with performance during a mountain biking descent under ecologically valid conditions. It is hypothesized that variations in performance time on a mountain bike descending track could be better explained by a new normalized brake work than by traditional brake metrics of relative brake work, brake time, or relative brake power, henceforth signifying the practical relevance of the algorithm in question.

2. Methods

2.1 Participants and Task

Nine nationally competitive mountain bikers (mean ± SD: age = 25.6 ± 3.6 years; body mass = 77.4 ±11.6 kg; height = 177.2 ± 11.2 cm) volunteered to take part in this study. Riders were asked to ride as quickly as possible on a track (Figure 1) that was chosen because of the descending nature which eliminated performance benefits due to pedaling (Miller, Macdermid, Fink, & Stannard, 2017). Participants completed three consecutive trials with 15 min epoch between. All participants were familiar with the track having previously ridden it on their own time. Informed consent was obtained prior to testing, and the methods used for testing were approved by Massey University's Human Ethics Committee.

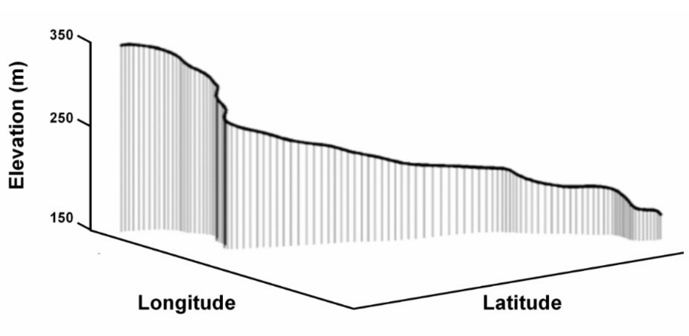

Figure 1: Elevation profile of the descending track used for testing in this study. The total distance was 1.01 km with a total elevation loss of 165 m (average gradient of -16.3%). This track was chosen based in its previous use which indicated that performance time was not dependent on propulsive work.

2.2 Apparatus

Prior to each test session, each participant was weighed while wearing cycling apparel, which included clothing, helmet and shoes. Participants all rode the same mountain bike (Trance 1, Giant Bicycles, New Zealand), which had suspension adjusted to manufacturer specifications pre-testing and had tires inflated to a standardized pressure (Macdermid et al., 2015). The bike was outfitted with a custom designed brake power meter (detailed in Miller, Fink, Macdermid, Perry, & Stannard, 2018) that continuously sampled and recorded at 128 Hz, and a propulsive power meter (S2275, Quarq, Spearfish, SD, USA) that recorded data at 1 Hz. Both the propulsive and brake power meters were calibrated prior to each test session, the Quarq by manually zeroed according to manufacturer specifications using a Garmin 510 (Garmin, Olathe, Kansas, USA) and the brake power meter by hanging known weights from the rim and recording the torque observed by the sensor. Using this method of calibrating the brake power meter, the brake power meter has been shown accurate to within 2% on the road and 5% on a dirt path (Miller, Fink, Macdermid, Perry, & Stannard, 2018). Brake power meter data were recorded on a stand-alone data logger (DATAQ UHS710; DATAQ Instruments, Akron Ohio, USA) attached to the bicycle handlebars while propulsive power was recorded on a portable cycle computer (510; Garmin Ltd., Schaffhausen, Switzerland). The total mass of the bicycle and all equipment was 18.64 kg; this is considerably heavier than a typical competition mountain bike, owing to the relatively large mass of the prototype brake power meter.

2.3 Procedure and Analysis

Brake power meter data was analyzed using Matlab R2011b (The MathWorks, Inc., Natick, MA, USA) to calculate variables of interest. Distance travelled during each trial was calculated by integrating the angular velocity of the front wheel over the descent and multiplying by the radius of the wheel plus tire. Performance time (s) was estimated as the time at which the distance travelled was equal to the distance of the track. There is a potential issue in that it assumes a given distance for the descent, which is not correct given that different paths on the track would result in different distances, but this method was chosen because it could be calculated without relying on GPS, which could not be accurately synced with the brake power meter. Brake power and brake work were calculated as explained in Eq. 1 and 2. Relative brake work was calculated by dividing the brake work over the entire descent by the mass of the rider plus bicycle. Any measurement that did not exceed 8 Nm was removed from analysis to reduce the effect of noise. Brake time (s) was the total time that either brake exceeded 8 Nm. Relative brake power (W/kg) was calculated as the product of relative brake work divided by brake time.

Normalized brake power (NBP), is brake power adjusted for kinetic energy, and was calculated instantaneously as (Eq. 6):

$$\mathrm{NBP}= \frac{\omega_f(\tau_f+\tau_r)}{\left(\frac{1}{2}mv^2\right)+\left(\frac{1}{2}\mathrm{I}\omega^2\right)}$$

where ω_f is the angular velocity of the front wheel, and τ_f and τ_r are the brake torque at the front and rear wheels respectively, m is the mass of the rider plus bicycle, I is the moment of inertia of the wheels, v is the instantaneous velocity, and ω is the instantaneous angular velocity of the wheels. The units for normalized brake power are 1/s.

Normalized brake power was integrated to calculate normalized brake work (NBW) across the descent (Eq. 7):

$$\mathrm{NBW} = \int_0^t \mathrm{NBP}\,dt$$

where normalized brake work is unitless.

As an additional method to visualize the data, histograms of normalized brake power were created by creating 10 bins, separated by 0.05 1/s. Values below 0.05 1/s were removed from the analysis, since these were extremely light braking events, while values above 0.50 1/s were included in the same bin due to their infrequent occurrence.

2.4 Statistical Approach

All trials for all participants were included in the analysis All statistical analyses were completed in GraphPad Prism 7.00 (GraphPad Software, San Diego California, USA). The mean ± standard deviation (SD) was calculated for performance time, relative brake work (brake work divided by the mass of the bicycle and rider), brake time, relative brake power (brake power divided by the mass of the bicycle and rider) and normalized brake work across all trials. The relationship between each of the variables and performance time was determined by applying a mixed model regression, with the y-intercept being a random factor. The fitted slope and y-intercept were used to calculate the degree of relationship between observed and fitted data for each of the variables. First, the overall sum of squares was calculated:

$$SSTO = \sum (Y_i - \bar{Y})^2$$

where Y is the variable of interest and $\bar{Y}$ is the mean of that variable. The error sum of squares was calculated using the fitted slope and y-intercept:

$$SSE = \sum \left(Y_i - \hat{Y}\right)^2$$

where $\hat{Y}$ is the fitted value. R2 was then calculated using

$$R^2 = 1 - \left(\frac{SSE}{SSTO}\right)$$

This calculation was performed for all variables to quantify the relationship between the variables of interest, coefficients of determination were also calculated between normalized brake power and relative brake work, brake time, and relative brake work. The alpha value for all tests was set to 0.05.

3. Results

The potential energy at the onset of the descent was 154,578 ±18,887 J, and participants completed an average propulsive work equating to 1,231 ± 3,217 J. Descriptive data for performance and braking variables are highlighted in Table 1. The relationship between performance time and relative brake work, brake time, relative brake power and normalized brake work, respectively, are reported in Figure 2A-D. Normalized brake work on the track used in this study displayed the strongest relationship with performance time ($r^2 = 0.912$, $p < 0.001$). Normalized brake work was also significantly correlated to measurements of relative brake work ($r^2 = 0.669$, $p < 0.001$), brake time ($r^2 = 0.7999$, $p < 0.001$), and relative brake power ($r^2 = 0.293$, $p = 0.0036$).

Table 1. Mean ± SD for performance and braking variables

Variable	Mean	SD
Performance time (s)	130.8	20.1
Velocity (km/h)	28.4	3.8
Relative brake work (J/kg)	676.0	152.3
Brake time (s)	62.3	21.1
Relative brake power (W/kg)	11.4	2.2
Normalized brake work	26.3	15.3

Note. Values were obtained from 27 descending trials on a mountain bike track that was not dependent on propulsive work

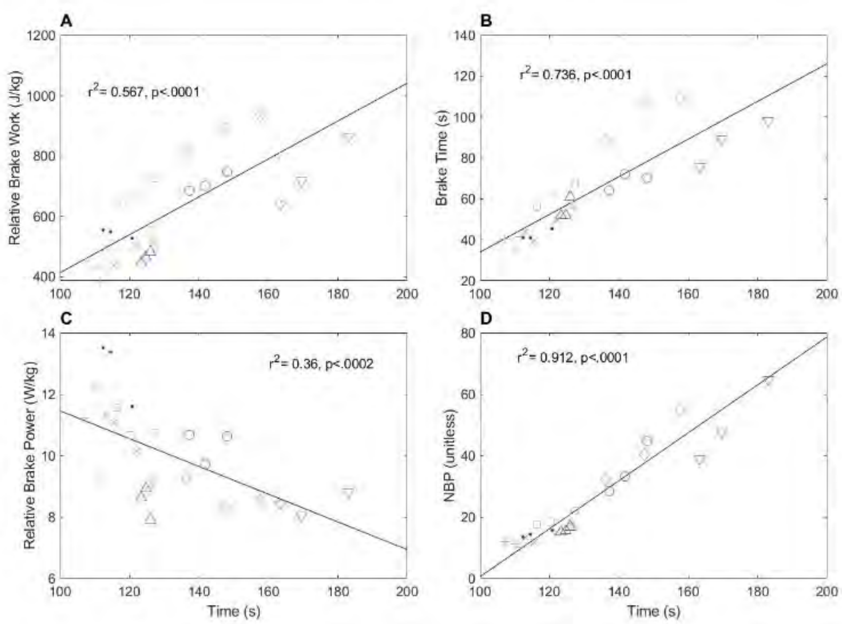

Figure 2: The relationship between performance time (s) on the mountain bike descent and A) relative brake work (J/kg); B) brake time (s); C) relative brake power (W/kg); and D) normalized brake work. The symbols and colors represent different riders.

To illustrate differences between skill levels, one trial was selected each from a high-performer (performance time = 115.4 s; normalized brake work = 13.1; relative brake work = 529.1 J/kg) while another was selected as that of a low-performer (performance time = 169.9 s; normalized brake work = 43.0; relative brake work = 966.5 J/kg). The relative brake power and normalized brake power from a small section of these trials are highlighted in Figure 3, which was chosen due to clear visual differences for each of comparison. From each entire trial, a histogram was created to indicate the magnitude of normalized brake power as a percent of brake time (Figure 4). What can be seen from these figures is that the high-performer was generating less normalized brake power during the same section of the descent (Figure 3). Moreover, when looking across the entire descent (Figure 4), the low performing rider spent a greater percentage of the braking time with high normalized brake powers.

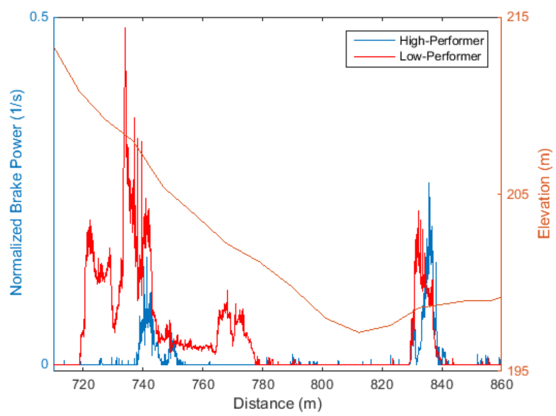

Figure 3: Graphical representation of normalized brake power (1/s) across a 150 m portion of the descent from one trial each by a high-performing and low-performing mountain biker. The normalized brake work was 0.13 and 0.80 for the high-performer and low-performer, respectively. The time to complete this section was 14.72 and 18.22 s for the high- and low-performer, respectively, which equated to 10.91 and 8.23 m/s, respectively.

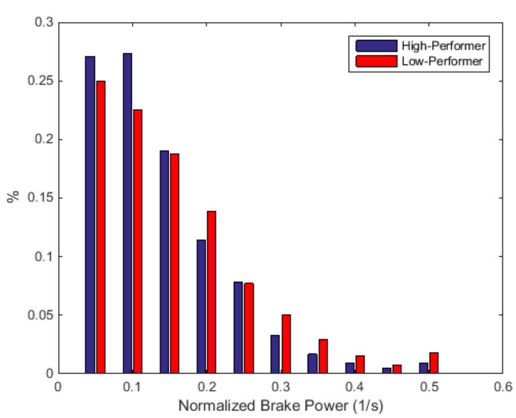

Figure 4: Frequency distribution of normalized brake power (1/s) comparing a high- and low-performing mountain biker.

4. Discussion

Braking has been identified as an important factor for performance in mountain biking; however, the exact relationship between braking and performance is difficult to confirm (e.g., Miller, Fink, Macdermid, Allen, & Stannard, 2018; Miller et al., 2019). This is the first investigation to utilize an algorithm to normalize brake power as a proportion of the kinetic energy of the bicycle-rider system, effectively scaling rider input to the brakes to both mass and velocity. It was hypothesized that normalized brake work would be more strongly associated with descending performance than traditional brake power meter metrics. Although relative brake work, brake time and relative brake power were all significantly associated with performance time on a mountain bike descending track (Figure 2A-C), normalized brake work explained more variance in descending performance time on the track used in this study (Figure 2D). By itself this result is important, as it indicates that normalized brake work could be used to quantify the contribution of skill to descending, and thus could be used to provide feedback about skill; this metric would be particularly useful in situations where the downhill, by its nature, requires significant propulsive work (unlike the downhill tested here).

Eq. 1-3 highlighted some of the complexities when utilizing traditional brake metrics such as relative brake work and relative brake power to explain variations in MTB descending time. The present method for calculating normalized brake power (Eq. 6) normalizes instantaneous brake power based on mass and velocity and is indicative of the proportion of kinetic energy removed at any time during braking. Once normalized brake power is integrated over time (Eq. 7), the resultant normalized brake work metric theoretically offers a broader representation of the conservation of kinetic energy with respect to braking than traditional brake measures. Since the potential energy of the bicycle-rider system is a product of the mass of the system times the height of the track and gravity, and there was negligible propulsive work completed by participants, the normalized brake work algorithm has sound theory for use in explaining the present descending performances.

The results presented in this study firstly reinforce the relationship between braking and mountain bike descending performance (Figure 2A-C). Indeed, the fastest performance times were associated with reduced relative brake work, reduced brake time, and increased relative brake power. These findings are not surprising, but support the qualitative importance of efficiently controlling the speed of the bicycle down the hill (Chidley et al., 2014; Hurst & Atkins, 2006) and reinforce earlier braking investigations (Miller et al., 2017; Miller, Fink, Macdermid, Allen, & Stannard, 2018; Miller et al., 2019). However, the main finding presently is that the normalized brake work metric was more strongly related to performance (Figure 2D) and can therefore explain more variation in descending performance than traditional measures from a brake power meter considered in isolation. This finding is promising because normalized brake work can indeed explain the variation in descending performance based on brake power meter data alone, thus eliminating the need for qualitative measures of descending performance or for other equipment. Moreover, the single metric output reduces the complexity of multivariate analyses of braking performance, which eliminates a potential barrier to use of the brake power meter for skill improvement.

Finding the most appropriate variable to provide feedback to riders is complicated by the correlations between normalized brake work and other braking variables measured in the study (e.g. brake time, relative brake work) as well as, potentially, braking variables not measured in the study (e.g., location of the braking events). One factor affecting performance is the location of the braking, which has been previously identified as a major difference between experienced and inexperienced riders (Miller, Fink, Macdermid, Allen, & Stannard, 2018). This factor that could likely benefit from visual inspection and should be explored further. Another braking factor affecting descending performance in the shape of the braking curve, as can be seen in Figure 3. A late-braking strategy is displayed by the high-performing rider, and acts to reduce performance time since a greater proportion of the time is spent moving more quickly. While the shape of the braking curve may indeed affect performance, the shape cannot be understood solely by looking at normalized brake work and may likely rely on visual inspection. Similarly, line choice likely factors into performance differences as well. Firstly, these could be analyzed based on GPS position, though these devices lack some resolution (Coutts et al., 2010). Furthermore, it is likely that there is an interaction with other elements of skill, particularly with the path chosen to go around corners, that will affect braking. For example, by changing the path going around a corner, the radius of the turn, and therefore the centripetal force required to make the turn at a given velocity, will change. Thus, changes in path (or line around a corner) will likely play a role in determining how much braking is necessary for the corner, which will in turn be reflected in the braking metrics. These complications are acknowledged, and future research will have to explore these relationships in greater detail. Nevertheless, even with these limitations, normalized brake power is useful as a way of quantifying aspects of skill related to the control of velocity during descents.

Because the study of braking in mountain biking is a relatively recent subject of study, at present we can only give suggestions for how normalized brake power could be used: research along these lines is continuing. One thing that is clear is that what constitutes a good normalized brake power will depend on the course that is being ridden: a straight line gentle descent will require little, if any, braking and therefore a normalized brake power of close to 0 for riders of any skill level; a very technical descent, requiring many sharp turns, on the other hand, will require a larger normalized brake power for even the most skilled rider. For this reason, it is recommended that comparisons only be made between descents of the same trail. By adjusting brake power for both mass and velocity, however, comparisons between individuals can be made, and also within the same individual between different runs (e.g., Miller, Fink, Macdermid, Allen, & Stannard, 2018; Miller et al., 2019, although these studies predated the normalized brake power).

Normalized brake work can also be used for entire descents, but could also be broken down for individual braking events. By calculating a normalized brake work for each corner or each braking event, and comparing the normalized brake work for each braking event to either other riders, or to the rider's previous descents, normalized brake work could be used to identify potential problem areas on the course. For example, Figure 3 shows a high performing (blue) and low performing (red) rider on the same section of the course. This section contains two turns, and therefore two braking events. There was little difference between the two riders on the second braking event, suggesting that braking event was not a problem for the low-performing rider on that turn. On the first braking event, however, there were large differences between the two, which would indicate the low performing rider could improve performance by concentrating on that particular braking event or turn. That information, by itself, could be useful but when combined with GPS or video, the exact nature of the problem (e.g. incorrect line leading into the turn, requiring more braking, braking past the apex of the turn, etc.) could be explored in more detail.

Development of a brake power meter, and identification of relevant metrics to describe braking, also raises the possibility for studies of the visual (and potentially other perceptual) information used to guide braking. Control of braking has been studied using an ecological framework (e.g. Fajen, 2005; Fajen, 2008; Lee, 1976; Yilmaz & Warren, 1995), but these studies have examined the case where the person is coming to a complete stop. In mountain biking, the goal is to move around a corner as quickly as possible, and only rarely coming to a complete stop. Because the goal is different, the proposed models do not apply, and the tau-based control (e.g. Lee, 1976; Yilmaz & Warren, 1995) must be modified. Given the nature of the task, it seems likely that the affordances involved must be directly incorporated in the control laws governing braking (e.g., Fajen, 2007). At present, no existing models for the control of braking appear to be sufficient for explaining the control of braking in mountain biking, but this is an area that could be further explored.

This study shows that the normalized brake work algorithm has sound theoretical reasoning for use in comparing brake data between riders travelling at different speeds. Normalized brake work can describe more variation in descending performance than other braking measures, which gives the brake power meter greater utility as a training tool. It is recommended that training interventions be utilized to enhance the braking patterns of low-performing mountain bikers, which should come as a benefit to their normalized brake work.

Conflict of Interest

Matthew Miller and Philip Fink are co-inventors of the brake power meter and are actively involved in commercializing the device.

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Effects of 15-mins of electroencephalographic neurofeedback on time perception and decision making in sport

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ABSTRACT

Our perception of time influences the critical decisions that we make on a daily basis. Time perception may also influence decision making and performance in sport. A lengthened perception of time, such as feeling that one is performing in slow-motion, may be associated with improved sport performance. This experiment reports the first examination of electroencephalographic (EEG) neurofeedback as an intervention designed to lengthen perceived time and improve decision making in sport. Thirty-one participants were randomly assigned to a neurofeedback group or a control group. They completed pre-test and post-test assessments of time perception and decision making in response to soccer penalty video clips played at a variety of speeds. In between, they underwent a 15-min neurofeedback intervention where they were trained to increase EEG theta and alpha power (neurofeedback group) or received sham training (control group). Results revealed that the neurofeedback intervention yielded a selective increase in EEG alpha power among members of the neurofeedback group. However, this had no effect on perception of time, and no beneficial effects on decision accuracy or decision response time. Several interpretations of the possible relationships between time perception, brainwaves and decision making in sport are discussed. Decision response time improved from pre-test to post-test for all participants, evidencing the potential of video-based training as a tool to enhance decision speed. Our findings also establish that just 15-mins of neurofeedback can produce significant changes in EEG alpha power. This highlights the potential of neurofeedback as a time-efficient means of modifying cortical activity for research and applied practice.

1. Introduction

Perception of time is the internal experience of the speed at which time passes, based on the use of an internal clock in the absence of cues from external clocks (Meck, 2005). Humans use an internal clock to perceive time throughout their activities of daily living, and time perception informs critical decisions (e.g., when to cross the road; when to move to evade a predator) that can ultimately determine whether an organism survives (Healy, McNally, Ruxton, Cooper, & Jackson, 2013). In fact, time perception might be so important that it has influenced the evolution of some species. For instance, research examining flicker fusion frequency, a measure of the rate that light is processed by the brain, implies that some types of bird and many types of fly may perceive time to pass by slowly, allowing them to experience the world in slow motion, and increase their chances of escaping life-threatening situations such as a fly swatter (Boström et al., 2016; Healy et al., 2013). Time perception may also be malleable within a species; several studies have evidenced interventions and experimental manipulations to alter perception of time in humans (e.g., Droit-Volet, Fanget, & Dambrun, 2015). Following the fly swatter example, it is tempting to speculate that interventions to lengthen perceived time in humans might be beneficial for performance in time-limited situations such as reactive sports. This experiment provides the first examination of whether electroencephalographic (EEG) neurofeedback can alter cortical activity to influence time perception and decision-making performance in sport.

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1.1. Time Perception and Sport

Time perception may have considerable importance in sport. For instance, athletes often report feeling as though the game is moving in slow motion when they are performing well, and at a faster pace when they are performing badly. Former world number one tennis player Martina Navratilova described being in the zone as an experience where everything seems to slow down, and she described everything moving at a fast pace during poor performances (Witt & Sugovic, 2010). Following such anecdotal reports, Witt and Sugovic (2010) experimentally investigated the relationship between time perception and sport performance. Participants varying in skill (beginners to experts) returned tennis balls from an automatic ball feeder, and completed a time perception task requiring them to hold the space bar on a keyboard to reproduce the time interval that they perceived between the ball leaving the feeder and striking their racquet. In support of their hypotheses, results revealed that participants estimated the intervals to be longer on successful trials (i.e., where the ball was successfully hit to a target zone; better performance) than during unsuccessful trials (i.e., shots that missed the target; worse performance). However, a separate analysis of perceived net height also revealed a significant relationship whereby players with more successful shots perceived the net as lower. Thus, the lengthening of perceived time may not have been the sole cause of good performance.

Studies of decision making in sport have also provided evidence to indicate a potential relationship between perceived time and performance. For example, Lorains, Ball, and MacMahon (2013a) examined participants' perception of the speed of a series of Australian Rules Football video clips. Elite and sub-elite footballers watched clips of football games at six different speeds (0.75, 1.0, 1.25, 1.5, 1.75 and 2.0 times the regular speed) and rated how each clip felt on a 1-7 Likert scale anchored with "too slow" (1), "very game-like" (4), and "too fast" (7). Results revealed that the 1.25 and the 1.5 speed video clips were perceived to be the most game-like, providing indirect evidence that experienced footballers had a lengthened perception of time when responding to the videos.[1] Subsequently, in an intervention study, Lorains, Ball, and MacMahon (2013b) indicated that footballers who trained their decision-making by viewing 1.5 speed video clips improved their decision accuracy more quickly than those who underwent the same training protocol but using normal 1.0 speed clips. Together, these findings provide indirect evidence to indicate that time perception in dynamic sport scenarios may lengthen with experience, and that training in conditions that may alter time perception (e.g., viewing 1.5 speeded videos) can help to accelerate the development of decision making expertise. Collectively, the findings of Witt and Sugovic (2010) and Lorains et al. (2013a; 2013b) provide some foundations for the idea that interventions designed to modify time perception could benefit sport performance.

This could be especially true for reactive sports where decisions must be made under time pressure. Time pressure is the "subjective feeling of having less time than is required (or perceived to be required) to complete a task" (Ordóñez, Benson, & Pittarello, 2015, p. 520). In reactive sport tasks, like receiving a serve in tennis, or facing a penalty kick as the goalkeeper in soccer, relevant information (e.g., body position of server/kicker) must be detected and processed, a decision has to be made (e.g., move left/right), and the motor response (e.g., initiate swing/dive) must be programmed in a matter of milliseconds (Gorgulu, Cooke, & Woodman, 2019; Johnson, 2006). Intuitively, one can speculate that any means of lengthening perceived time in such situations could provide the player with an important perceptual advantage that could facilitate more accurate decisions and better performance. Lorains et al. (2013b) provide evidence that speeded video training could benefit performance, but the rationale for that experiment was borne more from theories of automaticity than from time perception research, and it is not known whether changes in time perception contributed to the improved performance outcomes. In this experiment we sought to examine and assess an intervention that was specifically designed to benefit performance by lengthening perceived time for sport-based decisions.

1.2. Time Perception Interventions

Before constructing an intervention aimed at lengthening perceived time, it is important to first consider the mechanisms underpinning how time perception judgements are built. The dominant models in the time perception literature argue that the key determinant of perceived time is the amount of attention that is devoted to the so-called internal clock at a given moment (Zakay & Block, 1997). Perceived time is said to be governed by the number of pulses accumulated by an internal clock system between the start and the end of each event of interest (Gibbon, 1977). For example, in the case of Witt and Sugovic's (2010) tennis study described above, the event of interest was the ball flight, so perceived time would be governed by number of pulses registered from the point at which the ball was ejected from the feeder until the point at which it struck the racquet. The greater ones' awareness of the internal clock, the more pulses are said to be registered, and longer event durations are perceived (i.e., perceived time is lengthened) (Zakay & Block, 1997). In contrast, if attention is directed away from the internal clock, less pulses are registered, and perceived time is reduced.

Based on this theorizing, the psychological practice of mindfulness meditation, where individuals purposely direct their attention inwards and towards bodily sensations such as breathing, has been identified as an intervention to draw attention towards the internal clock and alter perceived time. For example, Droit-Volet and colleagues (2015) revealed that after daily mindfulness meditation practice (20 mins) over five-weeks, human time perception was significantly lengthened; a temporal bisection task revealed that participants overestimated the interval between auditory tones after mindfulness training. This provides evidence that human time perception is malleable and highlights

[1]The 1.25 and 1.5 clips were shorter in duration than the normal 1.0 clips (e.g., a 6s video at normal 1.0 speed would have been just 4s in duration when played at 1.5 speed), yet these 1.25 and 1.5 speed clips were perceived to be of the normal game-like duration. Put simply, the experienced participants appeared to perceive that the speeded clips were of a longer duration than they actually were.

mindfulness as a candidate intervention to modify perceived time and benefit human performance. However, Droit-Volet et al. (2015) also revealed that a shorter mindfulness intervention (i.e., single 10-min session) had little impact on perceived time, thereby implying the need for extensive meditation practice for time perception effects to be realized. This is unfortunate and reduces the appeal of mindfulness as an acute intervention during competitive sport, where athletes require very brief interventions if they are to be used in-game (e.g., incorporated into a pre-shot routine). Fortunately, EEG neurofeedback represents an intervention that may be able to replicate the attentional and neurophysiological characteristics of meditation and thereby influence time perception during a game, without the need for extensive training (Ring, Cooke, Kavussanu, McIntyre, & Masters, 2015). An introduction to neurofeedback and a more detailed overview of the neurophysiological effects of meditation and how they could impact perceived time is considered next.

1.3. Time Perception and Neurofeedback

Neurofeedback involves recording and displaying an individual's brain activity in real time, while encouraging them to develop strategies to control their brain activity levels. For example, computer software can be programmed to reward a participant by displaying a positive image or emitting a pleasant sound whenever a desired pattern of activation is achieved. In this way, individuals can learn to recognize and volitionally produce desired activation levels via the principals of operant conditioning (Skinner, 1963). Moreover, with relatively little neurofeedback training, participants can learn to produce the desired brain states in-game, during pre-performance routines (Ring et al., 2015).

The recipe for how neurofeedback might be employed (i.e., what aspects of brain activity should be fed back) to lengthen perceived time in sport can be derived from previous studies of brain activity during mindfulness meditation. Many mindfulness experiments have employed EEG, a brain imaging method that involves measuring electrical activity on the scalp (Harmon-Jones & Peterson, 2009), to shed light on the brainwaves that occur during meditative states. A recent systematic review of 56 EEG and mindfulness experiments revealed distinct effects of mindfulness principally characterised by an increase in EEG power in the theta (proportion of brainwaves oscillating between 4 and 7 Hz) and alpha (proportion of brainwaves oscillating between 8 and 12 Hz) frequency bands (Lomas, Ivtzan, & Fu, 2015). For example, Lagopoulos et al. (2009) compared EEG activity during 20 minutes of meditation with EEG activity during 20 minutes of quiet rest in a sample of 18 experienced meditators. Results revealed that there was a significant whole-brain increase in theta and alpha power during meditation compared to rest. EEG alpha power has an inhibitory function, with increases in alpha power said to inhibit activation, and decreases in alpha power said to increase cortical activation (Klimesch, Sauseng, & Hanslmayr, 2007). Increased alpha power has also been associated with the internalizing of attention (Cooper, Burgess, Croft, & Gruzelier, 2006). Increased tonic theta power may also associate with internalized attention and creative thinking, with theta waves characterizing the transition from wakefulness to sleep (Gruzelier, 2009; although note that the interpretation of theta remains a source of debate, see Klimesch, 1999). Accordingly, the increased theta and alpha power that are associated with mindfulness could explain how mindfulness meditation impacts our internal clock to modify perception of time. Specifically, the presence of increased EEG theta and alpha power during meditation could reflect more internalized attention towards the internal clock, thereby explaining how, in well-trained meditators, mindfulness can lengthen perceived time. These findings make a case for increased theta and alpha power being the targets for our EEG neurofeedback intervention.

Previous studies of neurofeedback in the motor performance domain have revealed that three hours of theta and alpha-based neurofeedback training was sufficient for golfers to learn to volitionally regulate these brainwaves during their pre-putt routine (Ring et al., 2015), while just 30 mins of alpha-based neurofeedback had a significant impact on subsequent motor performance (Sidhu & Cooke, 2020). This work demonstrates the potential of neurofeedback as an intervention that athletes can use to learn how to control their pre-performance brainwaves and potentially improve their performance in sport. However, no previous studies have examined the effects of neurofeedback on perceived time, and its subsequent effects on decision making, during reactive sports.

1.4. The Present Experiment

This experiment is designed to examine the effects of a brief EEG neurofeedback intervention to increase theta and alpha power on perception of time, and subsequent decision-making performance in reactive sport. Based on the research described above, we expected that: a) six 2.5 min neurofeedback sessions will be able to increase EEG theta and alpha power; b) this will lengthen perceived time viewing sport video clips; and c) this will improve sport-based decision making. To test these ideas, we adopted a mixed-model design where participants were assigned to either a neurofeedback group, or a control group, and completed a reactive soccer decision-making task and a time perception task either side of a 15-minute neurofeedback (or control) intervention. We hypothesized a series of interactions. First, we hypothesized group and session interactions for alpha and theta power; alpha and theta power were expected to be similar between the two groups at the start of the intervention before diverging over the six 2.5 min neurofeedback sessions (relative increase in power for the neurofeedback group). Second, we hypothesized a series of group and test interactions for time perception and decision-making variables. Specifically, we expected perceived time to be lengthened, decision accuracy to increase, and decision response time to decrease from pre-test to post-test to a greater extent in the neurofeedback than in the control group.

2. Methods

2.1. Participants

Thirty-one participants (15 male, 16 female; *M* age = 25.42, *SD* = 4.52 years) volunteered to take part in the experiment. We recruited participants via advertisement posters. All participants reported being free from illness and injury and were not taking any prescription medication (with the exception of the contraceptive pill) at the time of the experiment. All participants were familiar with the sport of soccer (i.e., had watched matches on television or live) and had varying levels of soccer playing experience (*M* soccer playing experience = 5.87, *SD* = 7.73 years; range = 0-23 years). We obtained informed consent from all participants. The experiment was approved by the University research ethics committee.

G*Power 3.1 power calculation software (Faul, Erdfelder, Buchner, & Lang, 2013) indicated that by adopting an alpha of .05 and a sample size of 31, the experiment was powered at .80 to detect between-within participant interactions for effect sizes exceeding f =.26 (i.e., medium-size effects) by mixed-model analysis of variance (ANOVA; Cohen, 1992). In a previous study of the effects of neurofeedback on motor performance, Cheng et al. (2015) reported a significant and large between-within participant interaction ($\eta_p^2 = .26$; performance improvement from pre- to post-intervention for neurofeedback group only). Accordingly, if similar effects were to emerge, our sample was adequately powered to detect them.

2.2. Design

We adopted a randomized placebo-controlled mixed-model design. The between-participant factor was Group. Participants were randomly assigned to either a Neurofeedback Group (*M* age = 26.25, SD = 4.41 years; *M* experience = 4.81, SD = 7.43 years) or a Control Group (*M* age = 24.53, SD = 4.63 years; *M* experience = 7.00, SD = 8.13 years)[2]. The within-participant factors were Test (i.e., pre-test, post-test), Video Speed (i.e., 0.75, 1.00, 1.25, 1.50, 1.75, 2.00), and Session (i.e., Baseline, Session 1, Session 2, Session 3, Session 4, Session 5, Session 6). All participants completed a soccer decision making task and a time perception task before (i.e., pre-test) and after (i.e., post-test) a 15-min neurofeedback (or control) intervention. The decision making and the time perception tests involved watching video clips of soccer penalties at six different speeds (i.e., 0.75, 1.00, 1.25, 1.50, 1.75 and 2.00). The neurofeedback (or control) intervention involved a baseline EEG recording and then six 2.5-min neurofeedback sessions (i.e., Baseline, Session 1, Session 2, Session 3, Session 4, Session 5, Session 6). More details about each of these factors are provided in the following sections.

2.3. Decision Making Task

We developed a bespoke soccer decision making task, informed by previous sport decision making research (e.g., Lorains et al, 2013a). Participants sat at a computer and watched video clips of a soccer player striking penalty kicks, filmed from the perspective of the goalkeeper. Each clip was paused at the critical decision point, just before the ball was kicked (Figure 1), and the participant was asked to indicate where they anticipated the ball would go in relation to the goal posts by pressing one of four keys on the keyboard (Key “W”= top left corner; “X” = bottom left corner; “O” = top right corner; “M” = bottom right corner). The letters were labelled with yellow stickers on the keyboard. Participants were shown eight clips (two clips of each of the four corners) at each of the six speeds (0.75, 1.0, 1.25, 1.5, 1.75- and 2.0-times normal speed) (Lorains et al., 2013a) to make 48 trials in total. The sequence of the videos and speeds were randomly presented. Participants were told to make their decision as fast as possible and were given a maximum of six seconds to respond to each trial.

Figure 1: A frame from one of the video clips depicting the point at which the video was paused, and a decision was required

2.4. Time Perception Task

Immediately after indicating where they anticipated the ball would go in relation to the goal posts (see Decision Making Task section above), participants were asked to rate how they perceived the speed of the video clip they just watched using a seven-point likert scale anchored at 1 (too slow), 4 (very game like) and 7 (too fast). The same video clip speed rating scale has been used in previous sport decision making research (Lorains et al., 2013a). This task differs somewhat from traditional methods of assessing time perception. For example, time perception can be assessed by reproduction timing, such as in Witt and Sugovic’s (2010) study where participants had to press and hold the space bar on the keyboard to reproduce the time interval they perceived between the previous ball release and racquet hit. Alternatively in a traditional temporal bisection task as employed by Droit-Volet et al. (2015), participants are presented with a short (e.g., tone sounding for 4 s) and a long (e.g., tone sounding for 8 s) interval standard, followed by comparison durations (e.g., 4.67-sec, 6-sec, 7.33-sec), and they judge whether each presented comparison was more similar to the short or the long interval standard (Grondin, 2010). However, parallels can be drawn to illustrate how our sport-specific task can be used to quantify sport-based time perception in the current study. For instance, in our task, the interval standard is drawn from memory, as the clips played in real time (i.e., 1.0 speed), since all participants were experienced in viewing televised soccer games at 1.0 speed. These clips are expected to be rated around 4 (i.e., very game like) on our 1-7

[2] Independent samples t-tests confirmed that the participant ages, $t(29) = -1.06$, $p = .30$ and experience, $t(29) = 0.78$, $p = .44$ did not differ between the neurofeedback group and the control group.

Likert scale.[3] Clips played at the other speeds are assumed to be less familiar as it is unlikely that participants are experienced in watching soccer clips at speeds other than 1.0, and hence, the 0.75, 1.25, 1.5, 1.75 and 2.0 speed clips can be considered a proxy for the comparison durations. We anticipate that it will be straightforward for participants to identify that, say, a 2.0 clip is shorter in duration than the 1.0 clips, and thereby give the 2.0 clip a higher score (e.g., 7 – too fast) on the rating scale. However, the key comparison on this metric is not the different ratings between clip speeds, but the changes in ratings at each speed from pre-test to post-test. If the neurofeedback intervention lengthens perceived time, we anticipate that all the clip speeds should receive lower speed ratings at post-test in members of the neurofeedback group. For example, if the 2.0 clips were rated at an average of 6.5 at pre-test, and 5.0 at post-test, this would indicate that time perception has been lengthened because these fast-paced short duration clips are perceived to be relatively slower and longer in duration at the post-test. We favoured this sport specific task over the more traditional reproduction or temporal bisection time perception paradigms because it allowed relatively seamless integration between the time perception and the decision-making tasks.

2.5. Neurofeedback Intervention

The decision making and time perception tasks described above were completed at pre-test and post-test, which were separated by the neurofeedback intervention. Participants received 15 minutes (six 2.5 min sessions) of genuine (neurofeedback group) or sham (control group) neurofeedback training. Cortical activity was recorded from the parietal midline of the scalp (i.e., Pz electrode site; Jasper, 1958) using an active electrode connected to a wireless 4-channel neurofeedback system (Brainquiry PET-4, Nijmegen, Netherlands). Additionally, an active electrode was placed over the orbicularis oculi muscle of the right eye to remove eyeblink artefacts, with reference and ground electrodes attached to the right and left mastoids (Ring et al. 2015). We focused our feedback on both theta (4-7 Hz) and alpha (8-12 Hz) power at the Pz site because increased power in these bands occurs during meditation, with the effects for alpha power being strongest over parietal areas (Lagopoulos et al., 2009). First, we measured baseline theta and alpha power. Participants were asked to fixate on a cross taped to the wall at eye level, for a period of five seconds while a computer running Bioexplorer software (Cyberevolution) extracted EEG theta (4-7 Hz) and alpha (8-12 Hz) power from the EEG signal. This process was repeated five times and the average of the recordings was used as their baseline theta and alpha power. Having established individual baselines, the procedure diverged for the neurofeedback group and the control group. For members of the neurofeedback group, a computer running Bioexplorer software extracted EEG theta and alpha power from the EEG signal and fed this back in the form of two bar graphs on a screen and an auditory tone (Ring et al., 2015). The graphs represented real-time theta and alpha power, with the bars moving up when power increased, and down when power decreased. Importantly, the tone was programmed to vary in pitch based on the level of alpha power and silence completely when both theta and alpha power were increased by 10% (neurofeedback sessions 1-3) or by 15% (neurofeedback sessions 4-6), relative to each participant's individual baseline. These thresholds were based on previous research documenting similar increases in EEG power during meditation (e.g., Cahn & Polich, 2006), and confirmed via pilot testing which established that they were achievable during our brief intervention. In addition to changing theta and alpha power by 10% (or 15%) the system also required <10 µV of 50Hz activity in the signal (i.e., low impedance) and the absence of eye-blinks, as detected by the electrode placed adjacent to the right eye, for the tone to silence. These control features helped ensure the signal was being regulated by cognitive processes and was not contaminated by muscular or eye-blink artefacts (Ring et al., 2015).

The neurofeedback was delivered to participants over six 2.5-min sessions, each separated by a 1-min break. Participants were seated, told that the graphs and the tone represented their brain activity, and told that their goal was to increase the size of both bar graphs to make the tone go silent. They were asked to try to recognize how to control the graphs and the tone with their thoughts. They were reassured that it should become easier with practice. Finally, they were told that the goal during each 2.5 min session was to increase the height of the bars in the two graphs and silence the tone as much as possible.

The procedure for members of the control group was identical except the graphs and tone supplied to them were not based on their brain activity. Instead, participants were played a recording of the graphs and tone from a matched participant from the neurofeedback group (Ring et al., 2015). Accordingly, unbeknownst to them, members of the control group received no systematic brain training.

2.6. Measures

2.6.1. Cortical Activity

Cortical activity was recorded during the neurofeedback intervention. Bioexplorer software applied bandpass filters to extract theta power (4-7 Hz) and alpha power (8-12 Hz) at a sample rate of 200 Hz. Power in the theta and alpha bands was then averaged for each of the 5s baselines, and for each of the 2.5 min neurofeedback sessions.

2.6.2. Decision Accuracy

Decision accuracy was measured by comparing participant's responses on the decision-making task (i.e., top left corner, bottom left corner, top right corner, bottom right corner) with the correct answer (i.e., the actual location the ball went in relation to the goal posts when each clip was played in full). Decision accuracy is expressed as a percentage. A score of 25% would be expected by chance, while scores greater than 25% reflect decision making above chance-level.

[3] We acknowledge that elite performers have been shown to rate clips at 1.25 to 1.5 speed as most game-like (Lorains et al., 2013a) when judging the clips against their real-game playing experience. However, the participants in the current study were not elite sport performers and had varied soccer playing experience. Therefore, we expect that most participants rated clips compared to how they recalled real-time soccer video clips (mostly consumed at 1.0 speed) rather than real-time soccer playing.

2.6.3. Decision Response Time

Decision response time was calculated as the time in milliseconds between the video pause and the button press response indicating which corner the participant expected the ball would go.

2.6.4. Speed Rating

We used speed rating on the time perception task as our proxy measure of perception of time. Reductions in speed rating scores on the time perception task from the pre-test to the post-test would indicate that videos were perceived as slower, and time perception was lengthened, after the interventions.

2.7. Procedure

Participants attended a single 75-min testing session. They were welcomed, briefed and gave their informed consent to take part, then demographic information was collected. All participants were then seated and fitted with a 4-channel wireless EEG neurofeedback system (PET-4, Brainquiry, The Netherlands). Active electrodes were placed at the parietal midline (i.e., Pz site, Jasper, 1958) of the scalp to record cortical activity, and over the orbicularis oculi muscle of the right eye to remove eyeblink artefacts, while reference and ground electrodes were attached to the right and left mastoids (Ring et al., 2015). We prepared the skin by lightly abrading over the mastoids and the right orbicularis oculi muscle with exfoliating paste, and with a blunt needle at the scalp site (Pz). The sites were then cleaned with an alcohol wipe, conductive gel was applied, and disposable spot electrodes (BlueSensor, Ambu) were placed and secured using tape and a lycra cap. The PET-4 wireless receiver was attached by an elastic and Velcro strap to the participant's right arm; this digitized the EEG signals at 24-bit resolution and transmitted them via Bluetooth at a sampling rate of 200 Hz to a laptop running Bioexplorer (Cyberevolution) software.

Following instrumentation, participants completed 24 practice trials of the decision making and time perception tasks to allow familiarisation with the task requirements. This was informed by pilot testing, which showed that a 24-trial familiarisation period allowed initially slow response times (as were typical in the first few trials) to stabilize, while not being so extensive as to induce fatigue. Participants were permitted a 2-min break after the familiarisation period. They then progressed to the Pre-Test, intervention, and Post-Test phases of the experiment. In the pre-test phase participants completed 48 trials of the decision making and time perception tasks as described above. After participants had made their decision making and speed rating responses at the end of each trial, a "get ready" prompt appeared on the screen, and the next trial automatically started after 2 s. E-prime software controlled the experiment and recorded all participant responses. On completion of the pre-test, participants underwent the neurofeedback (or control) intervention, as described above. Immediately after the intervention, participants completed the post-test phase, which was identical to the pre-test. Finally, the neurofeedback hardware was removed and participants were debriefed and thanked.

2.8. Statistical Analyses

2.8.1. Primary Analyses

We examined the effectiveness of our neurofeedback intervention by subjecting our measures of theta and alpha power to 2 Group (neurofeedback, control) × 7 Session (baseline, session 1, session 2, session 3, session 4, session 5, session 6) ANOVAs. Then, to examine our primary hypotheses concerning the effects of neurofeedback on time perception and decision making, we subjected our speed rating, decision accuracy and decision response time measures to 2 Group (neurofeedback, control) × 2 Test (pre-test, post-test) × 6 Video Speed (0.75, 1.00, 1.25, 1.50, 1.75, 2.00) ANOVAs. Significant effects were probed by polynomial trend analyses, and, in the case of 3-way interactions, by 2 Test × 6 Video Speed ANOVAs performed separately for each group.

2.8.2. Secondary Analyses

As a secondary aim, we also considered the effects of soccer playing experience on our key time perception and decision-making measures. While all our participants were experienced soccer spectators, 17 reported at least 1 year of regular soccer playing experience (M = 10.71, SD = 7.55 years), and 14 reported no soccer playing experience. Accordingly, separate from our main analyses of the effects of neurofeedback training, we examined the effects of soccer playing experience on speed ratings, decision accuracy and decision response time during the pre-test (i.e., before experimental grouping and interventions occurred) via 2 Experience (Yes, No) × 6 Video Speed (0.75, 1.00, 1.25, 1.50, 1.75, 2.00) ANOVAs for each measure. We also calculated the bivariate correlations between years of soccer playing experience and speed rating, and between speed rating and decision accuracy and decision response time at each video speed during the pre-test. Based on the research and our interpretation of the results of Lorains et al. (2013a; 2013b), our exploratory predictions were that the more experienced players would display lower speed ratings (indicating a longer perception of time) and better decision making performance (especially during higher speed clips). We also expected that speed ratings would display negative correlations with decision accuracy and positive correlations with decision response time (indicating longer perception of time correlating with better performance).

For both primary and secondary analyses the results of univariate tests are reported, with the Huynh-Feldt correction procedure applied for analyses that violated the sphericity of variance assumption. Due to software malfunction, speed ratings, decision accuracy and decision response time data were lost for one, two and three participants, respectively; occasional missing data are reflected in the reported degrees of freedom. Partial eta-squared is reported as a measure of effect size, with values of .02, .12 and .26 indicating relatively small, medium and large effect sizes, respectively (Cohen, 1992).

3. Results

3.1. Manipulation Check

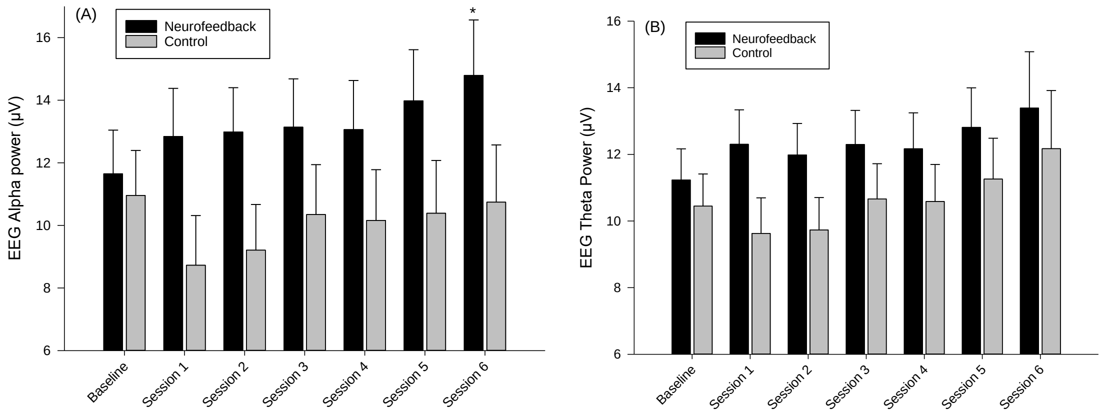

Figure 2: Alpha power (Panel A) and theta power (Panel B) as a function of Group and Session during the intervention phase of the experiment. Error bars indicate standard error of the means. * Indicates significant increasing linear trend for the Neurofeedback Group.

A 2 Group × 7 Session ANOVA for alpha power revealed no main effect for group, $F(1,29) = 2.22$, $p = .147$, $\eta_p^2 = .071$, a main effect for session, $F(4.51,130.68) = 2.69$, $p = .028$, $\eta_p^2 = .085$, $\varepsilon = .751$, and a marginal group × session interaction, $F(4.51,130.68) = 2.12$, $p = .074$, $\eta_p^2 = .068$, $\varepsilon = .751$. Polynomial trend analyses revealed that the main effect for session was characterised by an increasing linear trend, $F(1,29) = 5.69$, $p < .05$, $\eta_p^2 = .164$; alpha power increased from baseline to the final neurofeedback session. They also revealed that the marginal group × session interaction was characterised by a difference in the linear trend; the linear increase in alpha power across sessions was significant for the neurofeedback group, $F(1,15) = 5.83$, $p = .029$, $\eta_p^2 = .280$, and not significant for the control group, $F(1,14) = 0.76$, $p = .400$, $\eta_p^2 = .051$.

A 2 Group × 7 Session ANOVA for theta power revealed no main effect for group, $F(1,29) = 1.41$, $p = .245$, $\eta_p^2 = .046$, no main effect for session, $F(2.73,79.27) = 2.32$, $p = .087$, $\eta_p^2 = .074$, $\varepsilon = .456$, and no group × session interaction, $F(2.73,79.27) = .446$, $p = .703$, $\eta_p^2 = .015$, $\varepsilon = .456$. The effects of alpha and theta power are illustrated in Figure 2.

3.2. Speed Rating

A 2 Group × 2 Test × 6 Video Speed ANOVA for speed rating revealed no main effect for group, $F(1,28) = 0.56$, $p = .461$, $\eta_p^2 = .020$, or test, $F(1,28) = 0.10$, $p = .759$, $\eta_p^2 = .003$, but there was a main effect for video speed, $F(1.87,52.43) = 153.44$, $p < .001$, $\eta_p^2 = .846$, $\varepsilon = .374$. There was also a group × video speed interaction, $F(1.87,52.43) = 4.22$, $p = .022$, $\eta_p^2 = .131$, $\varepsilon = .374$. The hypothesized group × test interaction was non-significant, $F(1,28) = 0.00$, $p = .972$, $\eta_p^2 = .000$. No other significant effects emerged. Polynomial trend analyses revealed that the main effect for video speed was characterised by an increasing linear trend, $F(1,28) = 207.21$, $p < .001$, $\eta_p^2 = .881$; speed ratings increased from the 0.75 speed clips to the 2.00 speed clips. They also revealed that the group × video speed interaction was characterised by a difference in the linear trend, which was slightly stronger for the neurofeedback group, $F(1,14) = 163.96$, $p < .001$, $\eta_p^2 = .921$, than for the control group, $F(1,14) = 63.12$, $p < .001$, $\eta_p^2 = .818$. This shows that participants correctly rated the slower videos as "too slow" and the faster videos as "too fast" and the effect was highly significant for both groups. The means are illustrated in Table 1. Note that the 1.0 and the 1.25 speed clips yielded mean ratings closest to 4 and were thereby considered the most game-like.

3.3. Decision Accuracy

A 2 Group × 2 Test × 6 Video Speed ANOVA for decision accuracy revealed no main effect for group, $F(1,27) = 0.29$, $p = .593$, $\eta_p^2 = .011$, no main effect for test, $F(1,27) = 0.78$, $p = .386$, $\eta_p^2 = .028$, and no main effect for video speed, $F(5,135) = 1.05$, $p = .390$, $\eta_p^2 = .037$. The hypothesized group × test interaction was non-significant, $F(1,27) = 1.86$, $p = .183$, $\eta_p^2 = .064$, but there was a significant group × test × video speed interaction, $F(5,135) = 2.95$, $p = .015$, $\eta_p^2 = .098$. Separate 2 Test × 6 Video Speed ANOVAs were conducted for each group to decompose the 3-way interaction. They revealed that the test × video speed interactions were non-significant, but the effect size was marginally greater for the neurofeedback group, $F(5,65) = 2.17$, $p = .069$, $\eta_p^2 = .143$ than for the control group, $F(5,70) = 1.86$, $p = .113$, $\eta_p^2 = .117$. The means are displayed in Table 1.

3.4. Decision Response Time

A 2 Group × 2 Test × 6 Video Speed ANOVA for decision response time revealed no main effect for group, $F(1,26) = 0.50$, $p = .486$, $\eta_p^2 = .019$, a main effect for test, $F(1,26) = 5.10$, $p = .033$, $\eta_p^2 = .164$, and a main effect for video speed, $F(4.18,108.78) = 6.52$, $p < .001$, $\eta_p^2 = .200$, $\varepsilon = .837$. The hypothesized group × test interaction was non-significant, $F(1,26) = 1.45$, $p = .239$, $\eta_p^2 = .053$. No other significant effects emerged. Polynomial trend analyses revealed that the main effect for video speed was characterised by an increasing linear trend, $F(1,26) = 13.15$, $p < .05$, $\eta_p^2 = .336$; participants were generally able to respond to the slower videos more quickly than they responded to the faster videos. The main effect for test confirmed that participants were faster at making decisions in the post-test ($M = 1028.89$, $SD = 757.91$ ms) than in the pre-test ($M = 1235.08$, $SD = 774.39$ ms). The means are presented in Table 1.

Table 1: Mean speed ratings and decision-making performance as a function of Group, Test and Video Speed.

	Pre-Test						**Post-Test**					
Speed rating (1-7)	**0.75**	**1.0**	**1.25**	**1.5**	**1.75**	**2.0**	**0.75**	**1.0**	**1.25**	**1.5**	**1.75**	**2.0**
Neurofeedback Group	2.20	3.48$_{\dagger}$	4.03$_{\dagger}$	4.88$_{\dagger}$	5.41$_{\dagger}$	5.83$_{\dagger}$	2.48	3.48$_{\dagger}$	4.06$_{\dagger}$	4.77$_{\dagger}$	5.28$_{\dagger}$	5.67$_{\dagger}$
Control Group	2.91	3.89$_{\dagger}$	4.41$_{\dagger}$	4.80$_{\dagger}$	5.29$_{\dagger}$	5.41$_{\dagger}$	2.91	3.98$_{\dagger}$	4.35$_{\dagger}$	4.77$_{\dagger}$	5.13$_{\dagger}$	5.43$_{\dagger}$
	Pre-Test						**Post-Test**					
Decision accuracy (%)	**0.75**	**1.0**	**1.25**	**1.5**	**1.75**	**2.0**	**0.75**	**1.0**	**1.25**	**1.5**	**1.75**	**2.0**
Neurofeedback Group	46.42	51.79	50.00	55.36	53.57	56.25	50.89	46.43	55.36	41.96$_{a\dagger}$	48.21	47.32
Control Group	45.00	45.83	52.50	44.17	40.83	50.00	49.17	53.33	43.33	50.83$_{a}$	39.18	47.50
	Pre-Test						**Post-Test$_{a}$**					
Decision response time (ms)	**0.75**	**1.0**	**1.25**	**1.5**	**1.75**	**2.0**	**0.75**	**1.0**	**1.25**	**1.5**	**1.75**	**2.0**
Neurofeedback Group	914.87	1071.42	1062.96	1107.27	1052.50	1320.50$_{\dagger}$	855.84	1013.89$_{\dagger}$	897.41$_{\dagger}$	1034.99	1015.06	1135.42
Control Group	1162.72	1406.42	1456.79	1419.36	1357.46	1488.71	981.81	1073.69	1136.14	1036.87$_{a}$	1018.47	1147.10

Note: $_{a}$ indicates significant change ($p < .05$) from the pre-test. $_{\dagger}$ indicates significant change ($p < .05$) from the previous video speed.

3.5. Secondary Analyses

To explore the secondary aim concerning the effects of soccer playing experience on our key time perception and decision-making measures we conducted 2 Experience × 6 Video Speed ANOVAs on the pre-test speed ratings, decision accuracy and decision response times. Analyses confirmed the previously described main effects of video speed on speed rating and decision response time (F's > 3.72, p's < .001, η_p^2's > .12); speed ratings and response times both increased from the slowest (0.75) to the fastest (2.00) video clips. There was no main effect of video speed on decision accuracy, $F(5,135) = 1.05$, $p = .39$, $\eta_p^2 = .04$, there was no main effect of experience on any of the variables, F's < 0.64, p's > .43, η_p^2's = .02, and there were no interaction effects, F's < 0.56, p's > .56, η_p^2's = .02. Means are presented in Table 2. Correlation analyses performed at each clip speed yielded non-significant positive correlations between experience and speed rating (r's = .01 - .20, p's = .29 – .98), non-significant and mixed positive and negative correlations between speed rating and decision accuracy (r's = -.19 - .26, p's = .19 – .97), and non-significant positive correlations between speed rating and decision response time (r's = .06 - .26, p's = .17 – .77). In sum, experience did not correlate with speed rating, and speed rating did not correlate with decision making performance. Those who had some soccer playing experience tended to perform a little better on the decision-making variables than their non-soccer playing counterparts (Table 2), but this was not statistically meaningful. The overall consensus is that experience appeared to have little bearing on the results of this experiment.

4. Discussion

This experiment was designed to examine the effects of a brief EEG neurofeedback intervention on brainwaves, time perception and decision making in sport. We expected that: a) six 2.5 min neurofeedback sessions would increase EEG theta and alpha power; b) this would lengthen perceived time viewing sport video clips; and c) this would improve sport-based decision making. Our results as they pertain to each of these predictions are discussed in the following sections.

4.1. Neurofeedback Manipulation Check

To establish the effectiveness of our brief neurofeedback intervention in modifying EEG theta and alpha power, we expected to reveal group and session interactions characterised by a selective increase in EEG theta and alpha power over the course of the intervention for the neurofeedback group only. We revealed partial support for our hypothesis. Specifically, there was a marginal group and session interaction for EEG alpha power, and follow-up planned polynomial contrasts confirmed that there was a significant increase in alpha power across the intervention sessions for members of the neurofeedback group only. This provides encouraging evidence that brief neurofeedback interventions can reliably modify brainwaves and replicate the pattern of increased alpha power that occurs during mindfulness in trained meditators, but in a more time-efficient manner (cf. Droit-Volet et al., 2015). By increasing alpha power, we can speculate that members of our neurofeedback group should have been able to inhibit the processing of environmental stimuli and experience a progressively more internalized state over the course of their neurofeedback intervention (Cooper et al., 2006; Klimesch et al., 2007), potentially drawing greater attention to their internal clock (Zakay & Block, 1997).

However, in contrast with our hypothesis, there was no group and session interaction for EEG theta power. While the effects of mindfulness on EEG theta power are widespread, they tend to be strongest over frontal regions, but we focused our neurofeedback on the parietal midline because that was revealed as the key location for meditation effects on alpha power (Lagopoulos et al., 2009). This could explain why our results failed to support our hypothesis for theta power. It would be interesting to replicate this experiment with two neurofeedback sites (i.e., parietal alpha and frontal theta) to optimize the feedback for both frequency bands. Notwithstanding, it is encouraging to note that such an acute intervention did deliver the expected alpha power effects, and the fact that theta power was also higher (albeit non-significantly – Figure 2B), does allow some confidence that the manipulation worked, and members of the neurofeedback group were in a different brain state than members of the control group ahead of the time perception and decision-making post-tests.

Table 2: Mean speed rating and decision-making performance as a function of soccer playing experience.

Experience Level	**Pre-Test**					
	0.75	**1.0**	**1.25**	**1.5**	**1.75**	**2.0**
Speed rating (1-7)						
Experienced	2.74	3.71†	4.29†	4.82†	5.40†	5.65
Inexperienced	2.32	3.65†	4.14†	4.88†	5.28†	5.57
Decision accuracy (%)						
Experienced	50.00	50.78	53.91	53.13	46.09	53.91
Inexperienced	40.35	46.15	48.08	45.19	48.08	51.92
Decision response time (ms)						
Experienced	908.74	1086.38	1191.22	1099.17	1060.35	1300.89†
Inexperienced	1158.86	1369.57	1280.38	1410.84	1321.01	1452.24

Note: † indicates significant change ($p < .05$) from the previous video speed.

4.2. Effects of Neurofeedback on Time Perception

We hypothesized that our neurofeedback intervention would lengthen perceived time, characterised by the neurofeedback group reporting lower speed ratings for the video clips than their control group counterparts during the post-test. This prediction was not supported as there was no group and test interaction for speed ratings. Our finding suggests that increase alpha and theta neurofeedback training has no impact on time perception. We chose increase alpha and theta as the targets for our neurofeedback intervention based on previous research demonstrating that these frequencies characterise mindfulness meditation (Lomas et al., 2015), and that mindfulness meditation can lengthen perceived time (Droit-Volet et al., 2015). It is possible that other aspects of mindfulness (e.g., reduced heart rate) are more important than brainwaves for mediating the effects of mindfulness on perception of time. This could be examined by future research.

Reassuringly, we did reveal a main effect for video speed. As would be expected, all participants accurately rated the 0.75 speed videos as the slowest, and the 2.00 speed videos as the fastest. We also revealed a group and video speed interaction where the neurofeedback group tended to rate the 0.75 videos as slightly slower and the 2.00 speed videos as slightly faster than the control participants. However, the difference between the linear trends displayed by the two groups was very small (control group η_p^2 = 82; neurofeedback group η_p^2 = .92) and was independent of the test factor so cannot be attributed to the neurofeedback intervention. Instead, this effect could be a result of random variation that may dissipate in a larger sample.

4.3. Effects of Neurofeedback on Decision Making

We hypothesized that decision accuracy and decision response time would improve from pre-test to post-test to a greater extent among members of the neurofeedback group than members of the control group. These hypotheses were not supported as there was no group and test interaction for either of these variables. There was a main effect of video speed for decision response time. As would be expected, participants were faster at making decisions in response to the clips at the slower video speeds than in response to clips at the faster video speeds. This is likely due to the extra time afforded to information processing during the slow-motion clips (Land & McLeod, 2000). There was also a main effect of test for decision response time. As would be expected, participants were faster at making decisions during the post-test, showing that decision making speed improves with practice (Mori, Ohtani, & Imanaka, 2002).

Interestingly, for decision accuracy, there was a three-way interaction effect showing that, if anything, decision accuracy decreased from pre-test to post-test, but only at the faster video speeds (especially the 1.5 speed) and for members of the neurofeedback group (Table 1). Thus, rather than the expected enhancement of decision making, it appears that there was a slight tendency for our neurofeedback intervention to prompt less accurate decisions during the faster video clips. While this observation clearly opposes our hypothesis, it must be noted that our performance-based hypotheses (i.e., neurofeedback would improve decision making) were contingent on support for our earlier hypothesis (i.e., neurofeedback would lengthen perceived time). Seeing as increased theta and alpha neurofeedback failed to impact time perception, we can reformulate our expectations concerning decision making. Specifically, our data show that members of the neurofeedback group entered the post-test with significantly increased EEG alpha power compared to the controls, possibly reflecting a more internally focused state (Cooper et al., 2006). The lack of time perception effects suggest that this was not focused on the internal clock. Instead, it may have primed decision reinvestment, where an internal self-focus may de-automate the decision-making process leading to inferior decision-making performance (Kinrade, Jackson, & Ashford, 2015). Alternatively, as reinvestment might be considered more likely to occur during slower than faster clips, a second possibility is that our alpha enhancing neurofeedback reduced cortical activity and encouraged a deepened state of relaxation (Nowlis & Kamiya, 1970). If members of the neurofeedback group were too relaxed at the post-test, this could have impaired their ability to concentrate, extract information, and make accurate decisions after the high-speed video clips.

In sum, had we ignored the enticing suggestion that increase theta and alpha power neurofeedback would lengthen perceived time, we could have formulated a different neurofeedback intervention specifically focused upon decision making and motor performance. For instance, previous studies have trained participants to decrease theta and/or alpha power prior to motor performance (e.g., Kao, Huang, & Hung, 2014; Ring et al., 2015) on the premise that these states may be associated with increased concentration, improved motor response programming, and an external focus of attention (Cooke, 2013; Cooke et al., 2014; Cooke et al., 2015). The demands of the task should be a very important consideration when formulating neurofeedback interventions; different protocols are typically prescribed for motor compared to cognitive tasks, and sometimes even within different classes of motor task (for review see Cooke, Bellomo, Gallicchio, & Ring, 2018). As the primary task here was a button press response, decreased alpha neurofeedback training to increase cortical excitability may have been the most obvious intervention to increase accuracy and decrease response times had our theorizing about time perception been put to one side. It would be interesting for future research to replicate and extend this experiment with a longer neurofeedback intervention and an additional decrease alpha and theta neurofeedback group to investigate this line of thinking.

4.4. Effects of Experience on Time Perception and Decision-Making

As an aside from our primary investigation into the effects of neurofeedback on time perception and decision making, our secondary analyses briefly considered the impact of soccer playing experience on our outcome measures. Lorains et al. (2013a) found that elite and sub-elite Australian rules football players responded differently to the speeded video paradigm, with elite players displaying improved decision accuracy and sub-elite players showing impaired decision accuracy with increasing video speeds. Novice players displayed lower decision accuracy scores throughout and were relatively unaffected by the changes in speed. The participants of the current study could not be classified based on their performance level, but we were able to dichotomize those with some soccer playing experience from those with no experience at all. Results revealed no main or interaction effects involving the experience factor in the current study. We did observe a main effect for decision response time, providing some evidence that performance of all participants was impaired with increasing video speeds. However, this effect did not manifest for decision accuracy meaning our performers most closely resembled the novice group from Lorains et al. (2013a) on the decision accuracy measure. Subtle differences in the decision and the response time recording methods employed here versus those employed by Lorains et al. (2013a) could explain why we revealed effects for decision time but not for decision accuracy, and why Lorains et al. (2013a) revealed the opposite pattern. Our decision accuracy measure was a forced choice between one correct and three incorrect options, whereas Lorains et al. (2013a) gave participants a relatively free choice of response and employed a points-based scoring system based on response quality. This may have rendered their accuracy measure more sensitive than ours. On the other hand, our response time measure required a simple button press whereas Lorains et al.'s (2013a) measure required participants to move and click a mouse, potentially involving different locations and movement times across trials. We may have benefited from lower between-trial variability and thereby higher sensitivity to temporal effects via our simple button press response. Irrespective of these methodological nuances, the pattern of stable accuracy and impaired decision response times at faster video speeds indicate that our participants more closely resembled those at the lower end of the skill acquisition continuum than elite athletes. Most importantly, this pattern occurred regardless of whether our participants reported having soccer playing experience or not, indicating that even our experienced participants may have been of a relatively low skill level. In future studies it would be advantageous to record soccer playing level (e.g., novice, sub-elite, elite) as well as experience as per Lorains et al. (2013a).

Our final set of analyses involving experience employed correlations to examine the prediction that experience would correlate with time perception, and the subsequent prediction that time perception would associate with performance. Results provided little evidence to suggest that experience on a task (in this case, soccer) serves to lengthen perceived time on that task. There were no significant correlations between experience and speed ratings at any video clip speed. There were also no correlations between speed ratings and either of the decision-making variables, providing little evidence to support our assertions that lower speed ratings, potentially indicating a lengthened perception of time, would be beneficial for performance. It is possible that lengthened time perception may come as a consequence of high-level performance rather than being something that causes high-level performance. For instance, the literature on embodied cognition and perception shows that participants in a rich vein of form demonstrate perception differences due to their superior form (Gray, 2014). The distance between the posts was perceived wider by American football kickers, and the size of the hole was perceived bigger by golfers, after (but not before) successful compared to unsuccessful performances (e.g., Witt, Linkenauger, Bakdash, & Proffitt, 2008; Witt & Dorsch, 2009). We previously described Witt and Sugovic's (2010) tennis study and speculated that the lengthened time perception that occurred after successful shots in that experiment may have contributed to the successful performance outcomes. However, it is possible that the direction of this relation was the other way around. Future research could conduct mediational analyses to probe the directionality of relations between expertise, performance outcome, and perception.

4.5. Limitations

The results of this experiment should be considered in light of some limitations. First, we did not measure EEG activity during the decision making and time perception tasks. Accordingly, although the EEG alpha data recorded during the neurofeedback intervention provide some evidence that cortical activity was different between the neurofeedback and the control groups at the end of the intervention, we do not know if these differences persisted throughout the post-test. Previous research has evidenced that changes in theta and alpha power induced during neurofeedback training can persist during post-training retention tests (e.g., Ring et al., 2015), but future research should measure cortical activity during post-tests to verify this assumption. Second, while we believe that parallels can be drawn between the sport-based speeded video paradigm that we employed to measure time perception, and the traditional temporal bisection task used by Driot-Volet et al. (2015) (see explanation in Methods section), we concede that our time perception measure remains somewhat atypical. Future research could adopt a range of reproduction or comparison timing measures to afford a more comprehensive assessment of perceived time in sport (Grondin, 2010). Finally, we recognise that our key prediction that lengthened time perception should benefit decision making is worthy of future scrutiny. Our prediction was based on evolutionary evidence showing that some species have developed a longer perception of time to provide a competitive advantage (Healy et al., 2013), and sport evidence suggesting that when time perception was longer, performance was better (Witt & Sugovic, 2010). However, there may be other factors to explain those previous results (e.g., Gray, 2014). For instance, while Lorains et al.'s (2013b) finding that speeded video training improved sport-based decisions may owe something to altered time perception, the performance benefits of the intervention were not attributed to changes in perceived time by the authors. Instead, Lorains et al. (2013b) argued that training with faster clips was beneficial because it permitted less time for information processing, and this was of benefit because it forced automatic decisions. In accord with this interpretation, Spitz, Moors, Wagemans and Helsen (2018) recently argued that watching clips in slow-motion can, in some cases, impair decision making. Interventions designed to modify perceived time may be considered in a different class of intervention to speeded video training. Time perception interventions like the one used here aim to instil a psychological strategy in training that, when learned, may transfer to match play to help participants cope with real game time pressure. In contrast, speeded video training appears more focused on promoting overreaching and adaption to more challenging conditions in training than one would routinely face in a game, potentially making real games feel easier. Future research could directly compare these two intervention types and explore whether time perception mechanisms underlie any performance benefits.

4.6. Conclusion

In conclusion, our experiment provides new evidence that just 15-mins of neurofeedback training can increase EEG alpha power and mimic the EEG alpha effects of mindfulness meditation. Accordingly, EEG neurofeedback could be of use as an alternative or supplemental method of replicating some of the effects of mindfulness in situations where there is insufficient time for a regular meditation session. However, neurofeedback had no impact on perception of time, and thereby failed to deliver any benefits for decision making during reactive sport. It remains for future research to further clarify the relationships between perceived time, decision making, and performance in sport. It is critical for neurofeedback interventions to be precisely tailored to the demands of the task at hand. While neurofeedback did not impact perceived time here, research is continually providing improved understanding of the brain states for optimized decision making, and thereby opening more avenues for new neurofeedback interventions targeted at improving sport performance. It is clear that neurofeedback can change brainwaves, and if the correct neurofeedback recipe can be programmed, we see considerable potential for neurofeedback as a valuable tool in the arsenal of skill acquisition practitioners in the years to come.

Conflict of Interest

The authors declare no conflict of interests.

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The relationship between the quantity of practice and in-game performance during practice with tournament performance in esports: An eight-week study

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ABSTRACT

This study aimed to examine the influence of the quantity of practice and the in-game performance during practice of professional esports players over an eight-week period immediately prior to a major esports tournament. Data was collected from 43 male professional esports players (age: 23.52 ± 2.50 y). A range of measures were collected on a weekly basis to describe the quantity of practice and represent in-game performance during practice. The relationship between practice and tournament performance was examined using individual linear mixed-effects models for each week prior to competition. In a final linear mixed-effects model which incorporated the relevant variables identified within the weekly models a significant average kill/death ratio + average score main effect on tournament performance was identified ($p < 0.001$, $R^2 = 0.30$). With every standard deviation increase in average kill/death ratio, there was a 7.94% increase in tournament score (95% CI: 3.86 – 12.18%, $t = 3.89$, $p \leq 0.001$). With every standard deviation increase in average score, there was a 6.40% increase in tournament score (95% CI: 2.40 – 10.56%, $t = 3.17$, $p = 0.003$). Overall, the quantity of practice and in-game performance during practice explained a small proportion of the variance in tournament performance. More specifically, the variables that were most associated with better tournament performance were kill/death ratio and the score obtained in practice during the lead up to competition. Interestingly, the quantity of accumulated and weekly practice had limited association with better tournament performance. Whether the association between practice and performance differs depending on players' expertise levels requires future research.

1. Introduction

Electronic sports (esports) involve individuals or teams of players who compete in video game competitions through human-computer interaction (Pluss et al., 2019). Participation in esports has risen exponentially over several decades, now with a population of over 100 million players worldwide (Novak, Bennett, Pluss, & Fransen, 2019). Despite high recreational participation rates, only a small number of players (a few hundred to several thousand depending on the video game) compete as professionals (Novak, Bennett, Pluss, & Fransen, 2020). While there are different esports genres (e.g., first-person shooters and multiplayer online battle arenas), esports players typically control an in-game avatar in a virtual environment to eliminate opposing players or achieve an objective (Kowal, Toth, Exton, & Campbell, 2018). Although the motivations (e.g., competition, passion, and social reasons) for pursuing a career in esports are documented (García-Lanzo & Chamarro, 2018; Kahn et al., 2015; Yee, 2006), the attainment of expertise in esports has received considerably less attention (Pluss et al., 2020) despite being investigated extensively in other fields such as music, sport, medicine, and academia (Ericsson, 2006; Ericsson, Krampe, & Tesch-Römer,

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1993; Starkes & Ericsson, 2003). At the forefront of expertise research are studies examining the practice activities (i.e., the frequency and type of practice) of an individual. Furthermore, researchers further explore how the amount of practice an individual engages in relates to attaining expertise (Baker, Côté, & Abernethy, 2003; Charness, Tuffiash, Krampe, Reingold, & Vasyukova, 2005; Côté, Baker, & Abernethy, 2007; Ericsson, 2006). Overall, extensive engagement in domain-specific activities (e.g., competition, organised training, and individual practice) is necessary to attain expert performance (Ericsson et al., 1993; Ward, Hodges, Starkes, & Williams, 2007). In many domains, the attainment of expertise can be influenced by the time engaged in practice (Baker, 2003; Baker, Cobley, & Fraser-Thomas, 2009; Mattson & Richards, 2010). As a result, researchers have focused on identifying which type of practice is most beneficial for developing expertise, as this information can assist with improving the effects of practice (Ericsson et al., 1993). Some researchers argue that practice must be deliberate and purposeful to attain expertise (Charness et al., 2005; Ericsson et al., 1993). Other authors argue that engaging in a wide range of activities, especially at an early age, is beneficial for the development of expertise as an enduring characteristic (i.e., sampling leads to longer careers) (Bridge & Toms, 2013; Goodway & Robinson, 2015). Despite this, it is generally accepted that the amount of practice an individual engages in is related to the attainment of expertise across many domains (Ericsson, 2020; Macnamara & Maitra, 2019).

Many studies typically observe practice over extended periods of time (e.g., months to years), practice can also provide acute (e.g., days to weeks) performance outcomes and performance improvements (de Bruin, Smits, Rikers, & Schmidt, 2008; Deakin & Cobley, 2003). Understanding the acute effects practice has on performance is beneficial for players and coaches to support training of specific skills (Gaspar et al., 2019). Furthermore, there is an inherent belief that future performance is influenced by training in the weeks immediately preceding competition, in other words, is you play as you train (Jones, Armour, & Potrac, 2003). Therefore, it is crucial to understand the relationship between practice and performance at an acute level, such as the preceding weeks of competition. Esports is novel in that practice settings (i.e., a mix of competitive game play under the same task constraints observed in competition and isolated practice activities) closely resemble competition contexts. This representativeness of practice environments is relatively uncommon in many other domains (Williams & Ericsson, 2005). For example, professional esports players undertake much of their practice by competing against other professional esports players in the same game under the same rules of competition, without requiring physical proximity due to the virtual nature of competition. An equivalent scenario in an association football context would be to have 22 of the world's best players from different teams and nations practice by competing in 90 minutes of 11 v 11 game-play on a full-sized pitch under the same rules of competition. As such, examining both the quantity of practice and the in-game performance measures during practice can help improve our understanding of the relationship between practice and performance. Therefore, the present study employed a prospective design to examine the quantity of practice and in-game performance measures during practice of professional players over an eight-week period immediately prior to a major esports tournament. Following previous work, it was hypothesised that the quantity of practice and in-game performance during practice in the weeks preceding a major competitive event will explain a proportion of the variance in tournament performance (Macnamara, Moreau, & Hambrick, 2016; Young, 1998).

2. Methods

2.1. Participants

Data was collected from 43 male professional esports players (age: 23.52 ± 2.50 y) from 14 separate teams competing in the major esports tournament (PGL Major Krakow 2017). The professional esports players compete on a full-time basis and represent a professional esports team at the highest level of competition in a first-person shooter video game (Counter-Strike: Global Offensive). The professional esports players within this competition were from North America (n = 14) or Europe (n = 29). The Institutional Ethics Research Committee approved this study.

2.2. Experimental procedure

The study used an eight-week longitudinal design to examine how the quantity of practice and in-game performance measures during practice were related to performance in a major esports tournament. In terms of the quantity of practice, the two main variables of interest were the time spent in-game and the time spent in competition. The time spent in-game typically involves practice focused on developing individual skills whilst time spent in competition is practice in a competitive team-based environment. The most common type of individual practice is practicing in deathmatch, which is a mode featuring instant respawns (allows players to respawn instantly after death) with the ability to purchase any primary and secondary weapons with no regards to the money economy, which is not evident in a competition setting. Each match lasts 10 minutes and the player with the highest points wins the round. Time spent in competition involves two teams (Terrorist and Counter-Terrorist) consisting of five players competing head to head in a 30-round match. The first team to score 16 points wins the game. After 15 rounds (half time), each team switches sides. Each round is one minute and 45 seconds long, however, if the Terrorists manage to plant the bomb then the round timer resets to 40 seconds. On average, a single competitive match will last approximately 40 minutes, though a competitive match can extend to over an hour if the match is close. If both teams reach 15 rounds each, the game will end in a tie.

This study used publicly available data from each player's official Steam® profile and a third-party webpage (https://csgo-stats.com). Data was collected at a standardised time on a weekly basis using a custom data scraping method developed in Python, which collated and stored all data into a Microsoft Excel spreadsheet. A labelling rule considered and discarded a data observation as an outlier when they were outside of the value associated with the values derived from multiplying each participants' interquartile range (IQR) by 1.5, upon which values beyond the 25th and 75th percentiles ± 1.5 × IQR (Hoaglin & Iglewicz, 1987; Hoaglin, Iglewicz, & Tukey, 1986). After discarding outliers, the current study used a total of 284 observations from 43 participant's (~6.6 observations per participant). Table 1 provides a description of the independent variables that were measured in the current study. These measures are commonly used for statistical analysis purposes to develop online rankings and determining match outcomes. The dependent variable was a player's standardized and normalised tournament score, which was calculated using the coefficient scores from a confirmatory factor analysis of the performance rating combined in a linear equation (Henderson et al., 2019). The following tournament performance metrics were introduced after being standardized and normalised into a quotient score with a mean of 100 and standard deviation of 15 (quotient score = 100 + (z-score*15): the kill/death difference quotient, kill/death ratio quotient, and solo rating (a proprietary calculation that assesses player performance) quotient. When controlling for low commonalities (< 0.4), the final tournament sum score was calculated as 0.977*kill/death difference quotient + 0.993*kill/death ratio quotient + 0.974*solo rating quotient. The Kaiser-Meyer-Olkin and Barlett's test demonstrated a considerable amount of variance that could be explained by the underlying factors (Kaiser-Meyer-Olkin measure of sampling accuracy: 0.70) and player performance could be presented as a single factor (Bartlett's test of Sphericity: $p < 0.001$).

2.3. Statistical analysis

Prior to analysis, the distribution of the dependent variable was visually inspected using boxplots and histograms. Additionally, homogeneity of variance was assessed at each level of analysis (e.g., dependent variable by player and dependent variable by week). Furthermore, collinearity of the independent variables was explored using correlation plots and correlation coefficients. A correlation coefficient cut-off of 0.80 was used to determine collinearity between independent variances (Grewal, Cote, & Baumgartner, 2004). In the case of multicollinearity, the independent variable with the strongest relationship with the dependent variable was retained. Seven separate linear mixed effects models (1 | Team) were applied to the data (one for each week of practice), each of which was developed using a step-up approach. This exploratory approach was used because no prior information was available about the relationship between practice and tournament performance in esports. In each step, a random intercepts null model was firstly specified. Then, subsequent models were compared with the null model or the previous step in the step-up approach where models with a significantly better model fit were retained; whereas, poorer fitting models were discarded according to the -2-log likelihood ratio test and associated *p*-value, Akaike Information Criterion explained variance, and conditional explained variance. Random slope

Table 1: A description of the quantity of practice and in-game performance measures

Independent variable	Description
Quantity of practice	
Accumulated time spent in-game (hours)	Total amount of practice that typically involves practice focused on developing individual skills
Accumulated time spent in competition (hours)	Weekly amount of practice that typically involves practice in a competitive team-based environment
Weekly time spent in-game (hours)	Total amount of practice that typically involves practice focused on developing individual skills
Weekly time spent in competition (hours)	Weekly amount of practice that typically involves practice in a competitive team-based environment
Weekly matches played (n)	Weekly number of matches played
In-game performance measures	
Accumulated win percentage (%)	Total number of matches won/number of matches played
Weekly win percentage (%)	Weekly number of matches won/number of matches played
Weekly kills (n)	Number of enemies eliminated
Weekly deaths (n)	Being eliminated by an enemy
Weekly kill/death ratio (n)	Number of kills/number of deaths
Weekly score (n)	A proprietary calculation built in-game that indicates how well you are doing compared to the other players in the same game
Weekly matches won (n)	The result of a match, whether it resulted in a win or a loss
Weekly most valuable player stars (n)	Given to one player that has contributed the most towards winning a round – generally obtained more kills, conceded less deaths, and planted/diffused bombs

models were considered but not introduced given the likelihood of overfitting in this sample. In the next step of the analyses, the variables that were associated with tournament performance in the weekly models were introduced into a final model that explored the effect of the accumulated eight-weeks of practice on tournament performance. For example, if kill/death ratio is associated with tournament performance in one of the weekly models, its central tendency over the eight weeks was introduced into the final model as a quotient score (scaled z-score). This transformation enabled interpretation of weekly variation in the relationship between the independent and dependent variables (i.e. whether the relationship between practice and subsequent performance was time-dependent) and which variables appeared to be associated with performance over a longer and cumulative time spans. Scaled z-scores (coefficients), standard errors, t-values, and 95% confidence intervals related to each significant independent variable were derived for further interpretation. Residual distribution plots associated Shapiro-Wilks tests, and Levene's tests were used to investigate how well the obtained models fit the data and whether homogeneity of residual variance was apparent. A criterion alpha level significance was set at $p < 0.05$. All statistical analyses were conducted using R statistical software (R Development Core Team, New Zealand).

3. Results

Figure 1 displays the average amount of time spent in-game and the average amount of time spent in competition each week out of competition (presented as mean ± SD). Table 2 displays the Akaike Information Criterion (AIC), explained variance (marginal R2), conditional explained variance (conditional R2), degrees of freedom (df) and the retained players (team) of the best fitting weekly models explaining tournament performance, as well as the best-fitting model with cumulative or average values over the eight-week period. At seven weeks out from competition, the linear mixed effects model identified a significant kill/death ratio + most valuable player stars main effect on tournament performance ($p \leq 0.001$). At six weeks out from competition, the linear mixed effects model identified a significant kill/death ratio main effect on tournament performance ($p \leq 0.001$). At five weeks out from competition, the linear mixed effects model identified a significant time spent in-game main effect on tournament performance ($p \leq 0.001$). At four weeks out from competition, the linear mixed effects model identified a significant kill/death ratio main effect on tournament performance ($p \leq 0.001$). At three weeks out from competition, the linear mixed effects model identified no significant main effects on tournament performance ($p > 0.05$). At two weeks out from competition, the linear mixed effects model identified a significant kill/death ratio main effect on tournament performance ($p \leq 0.001$). At one week out from competition, the linear mixed effects model identified a significant kill/death ratio main effect on tournament performance ($p \leq 0.001$). In the average model, the linear mixed effects model identified a significant average kill/death ratio + average score main effect on tournament performance ($p \leq 0.001$). Table 3 displays the scaled z-scores (coefficients), 95% confidence intervals, p-value, t-value, obtained from best fitting models explained tournament performance each week out of competition. Also, Table 3 displays the best fitting models with the cumulative values over the eight-week period. In the average model, for every standard deviation increase in average kill/death ratio, there is a 7.9% increase in tournament score (95% confidence interval: 3.9 – 12.2, t = 3.89, $p \leq 0.001$). Furthermore, with every standard deviation increase in average score, there is a 6.4% increase in tournament score (95% confidence interval: 2.4 – 10.6, t = 3.17, $p = 0.003$).

Table 2: The effects of accumulated values and weekly values on tournament performance

	Best fitting weekly models explaining tournament score				
Models	**AIC**	**Marginal R^2**	**Conditional R^2**	**df**	**Players (team)**
Null: Score ~ 1 + (1 | Team)					
7 weeks out: Score ~ KD + MVP + (1 | Team)	-48.0	0.22	0.67	5	41 (14)
6 weeks out: Score ~ KD + (1 | Team)	-34.4	0.12	0.35	4	40 (14)
5 weeks out: Score ~ TSI + (1 | Team)	-37.4	0.17	0.31	4	40 (14)
4 weeks out: Score ~ KD + (1 | Team)	-43.0	0.18	0.47	4	39 (14)
3 weeks out: Null	N/A	N/A	N/A	N/A	N/A
2 weeks out: Score ~ KD + (1 | Team)	-36.0	0.12	0.25	4	41 (14)
1 week out: Score ~ KD + (1 | Team)	-37.1	0.09	0.15	4	40 (14)
Average: Score ~ Av KD + Av Score + (1 | Team)	-120.4	0.30	0.60	5	43 (14)

Note: AIC = Akaike Information Criterion, df = degrees of freedom, KD = kill/death ratio, MVP = most valuable player stars, TSI = time spent in-game, N/A = not applicable, Av = average. The term of players (team) refers to the number of players and (teams) observations after discarding outliers based on the labelling rule.

Table 3: The independent variables in the weekly models that were associated with better tournament performance

	Coefficient	95% CI	t-value	p-value
Intercept				
7 weeks out:	287.2	269.5 - 306.1		<0.001
6 weeks out:	290.4	276.5 - 304.9		<0.001
5 weeks out:	292.9	278.7 - 307.9		<0.001
4 weeks out:	290.2	274.8 - 306.4		<0.001
3 weeks out				
2 weeks out	290.3	275.6 - 305.8		<0.001
1 week out:	288.9	276.1 - 302.4		<0.001
Average:	291.24	275.57 - 307.80		<0.001
Kill/death ratio (n)				
7 weeks out:	3.28	0.02 - 6.87	1.847	0.073
6 weeks out:	5.51	0.87 - 10.37	2.337	0.496
5 weeks out:				
4 weeks out:	6.53	2.39 - 10.84	3.132	0.003
3 weeks out				
2 weeks out	5.49	0.75 - 10.45	2.277	0.029
1 week out:	4.56	0.07 - 9.24	1.994	0.054
Average:	7.94	3.86 - 12.18	3.885	<0.001
Most valuable player stars (n)				
7 weeks out:	5.36	1.78 - 9.06	2.964	0.006
6 weeks out:				
5 weeks out:				
4 weeks out:				
3 weeks out				
2 weeks out				
1 week out:				
Average:				
Time spent in-game (n)				
7 weeks out:				
6 weeks out:				
5 weeks out:	-6.14	-10.42 - -1.44	-2.553	0.019
4 weeks out:				
3 weeks out				
2 weeks out				
1 week out:				
Average:				
Score (n)				
7 weeks out:				
6 weeks out:				
5 weeks out:				
4 weeks out:				
3 weeks out				
2 weeks out				
1 week out:				
Average:	6.40	2.40 - 10.56	3.172	0.003

Note: CI = confidence interval. A blank row indicates that there is no significant association ($p > 0.05$) with tournament score.

4. Discussion

The current study examined the quantity of practice and in-game performance during practice of professional esports players over an eight-week period in the lead up to a major esports tournament. Overall, the quantity of practice and in-game performance during practice explains a small proportion of variance in tournament performance. More specifically, the variables that are most associated with better tournament performance are kill/death ratio (number of kills/number of deaths) and score (indicates how well you are doing compared to the other players in the same game) during the lead up to competition. When analysing the practice at a weekly basis, most of the variables associated with better tournament performance were measures of in-game performance during practice, rather than the quantity of practice. Evidentially, accumulated (total time spent in-game and total time spent in competition) and weekly (weekly time spent in-game and weekly time spent in competition) durations of practice had limited association with better tournament performance in professional esports players. Similarly, Macnamara et al. (2016) demonstrated that the accumulated quantity of practice accounted for 1% of the variance in performance among elite athletes in team and individual sports. Furthermore, Young (1998) reported that the total sum of all accumulated practice had no significant correlation ($r = 0.12$) with performance for middle distance runners. As such, this finding does not provide support that individual differences, even among professional esports players, are closely related to the accumulated quantity of practice (Ericsson, 2006; Ericsson et al., 1993; Ward et al., 2007). However, practice which is deliberate and purposeful is likely necessary to reach a high level of expertise in esports. Despite this, it is apparent that there is more to differentiate between performance than the quantity of practice at the professional level. As such, tracking the quantity of practice over a longitudinal period with different expertise levels (i.e., semi-professional, amateur, and recreational) remains an area for future research.

Esports practice is primarily conducted in an environment whereby the players actively respond to a task with an explicit goal, receive immediate formative feedback, and repeatedly perform the same or similar tasks (Ericsson, 2020; Macnamara & Maitra, 2019). The time spent in-game typically involves practice focused on developing individual skills, whereas the time spent in competition involves practice in a competitive team-based environment. It is suggested that engaging in both types of practice is beneficial for the development of expertise. It is likely that involvement in these types of practice present esports players with different action sequences and situational contexts (Côté et al., 2007; Davids, Button, & Bennett, 2008). However, during the lead up to competition, the amount an individual engages in practice (average of 32 hours per week) is unlikely to lead to better tournament performance. Perhaps better tournament performance reflects having a specific focus during practice, whereby the goal is to maximise the number of enemies they eliminate and minimise the amount of times they are eliminated by an enemy. Practicing in this manner is largely implicit driven and players must self-discover their own solutions to the task, which may

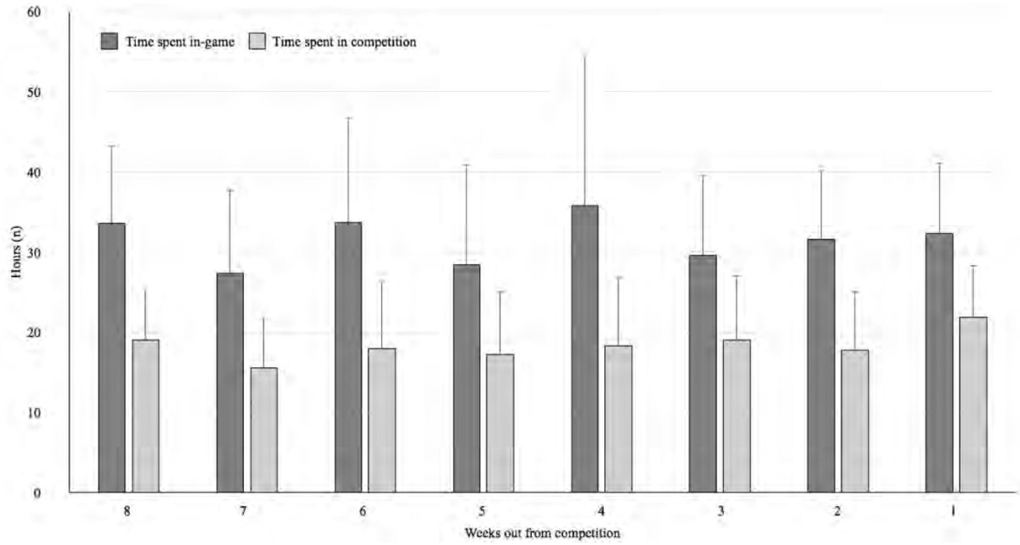

Figure 1: The average amount of time spent in-game and the average amount of time spent in competition each week out of competition (presented as mean ± SD)

explain the acute effects that practice has on tournament performance (Côté, Baker, & Abernethy, 2003). However, future research is needed to support this hypothesis as the specific goals and motives of esports players during practice were not measured within the present study.

The kill/death ratio of a player was the most significant variable associated with tournament performance over the eight-week period. Furthermore, the kill/death ratio is often seen as one of the most effective ways to evaluate an individual's in-game performance in many different esports genres, in particular, first-person shooters (i.e., Counter-Strike: Global Offensive, Call of Duty, and Overwatch). Players outperforming their opponents is achieved by a kill/death ratio greater than 1.0, whereas a player underperforming will have a kill/death ratio of less than 1.0. Despite being an indicator of individual performance, considerations have been raised about the use of kill/death ratio as a performance indicator within the esports field. The main consideration is that it favours players who play fewer rounds in a match with fewer deaths will result in a higher kill/death ratio. Kill/death ratio would suggest players had similar performance if player A had 13 kills, 6 deaths (kill/death ratio = 2.17) in a match of 18 rounds and player B had 37 kills, 17 deaths (kill/death ratio = 2.17) in a match of 30 rounds. Interestingly, there were no cases of collinearity between the variables of weekly kills, weekly deaths, weekly kill/death ratio, weekly matches played, and weekly rounds played. Each of the variables of interest measure sufficiently different constructs, which provides evidence to dismiss the consideration that kill/death ratio favours players who play fewer rounds in a match with fewer deaths will result in a higher kill/death ratio. Furthermore, to perform better in the tournaments you need to be a better performer as the better performers in the tournament were also the better players in the lead up to the competition. In terms of understanding the attainment of expertise in esports, kill/death ratio offers a simple metric to objectively quantify in-game performance during practice for all expertise levels. However, it is important to note that within team-based environments, each player will have a specific role. For example, an entry fragger plays aggressive and is likely to be eliminated first, which often results in a lower kill/death ratio. Whereas a lurker plays slow and calls out opponents' positions, which often results in a higher kill/death ratio.

4.1. Limitations and future directions

First, this study did not account for locational or environmental factors that may influence performance. Previously, it has been demonstrated that travel and environmental conditions can either positively or negatively impact performance (Waterhouse, Reilly, Atkinson, & Edwards, 2007). As such, it is possible that prolonged travel may impart a physical and cognitive toll on a player, which may adversely affect performance in competition. Second, performance was only examined in one major esports tournament (PGL Major Krakow 2017). Future research should consider cross-validating these findings in other tournaments and other expertise levels (e.g. semi-professional and amateur esports players) to test the statistical model. Third, data was only collected from each player's main profile. As such, any additional practice on alternative accounts (i.e., smurf accounts – an alternative account used by a known or experienced user in order to deceptively self-present as less experienced) was not accounted for within the present study and would be worthwhile to account for in future research. Furthermore, whether players spent time playing other games during the lead up to the competition was not recorded, which may limit the amount of time they have to practice. In addition, the potential of skill transfer from other games (e.g., first-person shooters such as Overwatch and PUBG) remains an area of future research to aim to quantify (Eccles & Feltovich, 2008). Fourth, a large proportion of the variance is also explained by the random effect (team) in this study. This means that a considerable amount of variance is explained by which team the player belongs to, which is reasonable because when a player's teammates obtain kills, it means there are fewer opponents available to kill the player, and it allows the player to move more easily into favourable positions and obtain subsequent kills themselves. Therefore, team selection was likely the largest contributor to an individual player's tournament performance, hence future research should further explore this interaction. An example of this would be to explore which variables (e.g. interpersonal skills and psychological traits) may be considered in team selection and how these factors may also be related to tournament performance.

5. Conclusion

This study examined the quantity of practice and in-game performance during practice of professional esports players over an eight-week period in the lead up to a major esports tournament. Overall, the quantity of practice and in-game performance during practice explains a small proportion of the variance in tournament performance. More specifically, the variables that are most associated with better tournament performance are kill/death ratio and score. Interestingly, the quantity of accumulated and weekly practice had limited association with better tournament performance. Although practice which is deliberate and purposeful is likely necessary to reach a high level of expertise in esports, it is apparent that there is more to differentiate between performance than the quantity of practice at the professional level. Therefore, tracking the quantity of practice over a longitudinal period with different expertise levels remains an area for future research.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that would be construed as a potential conflict of interest.

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Neuropsychological functioning in athletes with untreated concussion at moderate elevation

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ABSTRACT

Concussion causes varying degrees of brain damage in athletes, and the neuropsychological consequences of concussion or incomplete recovery can impede skill acquisition. This study examined the neuropsychological recovery from concussion in athletes at moderate elevation, 80% of whom did not seek treatment for their concussion. We collected data on concussions sustained at or around 1966 m among university athletes. American football players at New Mexico Highlands University (N = 13) were administered a 40-minute neuropsychological battery to examine domains affected by concussion such as attention, memory, information processing speed, executive functioning, and depressive symptoms at two time points, before and after the 2016 football season. In total, there were 5 concussed athletes (assessed m = 45.6 days post-injury) and 8 non-concussed control athletes. A repeated-measures ANOVA showed a significant group-by-time interaction for depression, F = 6.335 (p = .029), with concussed athletes showing significant increases in depressive symptoms. Repeated-measures ANCOVAs (controlling for depressive symptoms) of the four athletes who did not seek treatment showed significant group-by-time interactions, with concussed athletes experiencing significant slowing in processing speed F = 26.51 (p = .001) and declines in verbal learning, F = 6.54 (p = .034). Additionally, two athletes (one who sustained a concussion and one who did not) were re-administered the battery mid-season, within 7 days post-injury; the concussed athlete experienced acute deficits in most domains and demonstrated incomplete recovery on measures of depression, verbal learning, and switching. These results indicate that untreated concussions sustained at moderate elevation may not fully recover within the frequently cited 10-day window, and suggest the need for future research into the role of both concussion treatment and elevation in concussion recovery prognosis.

1. Introduction

A concussion is a change in awareness or consciousness caused by a physical impact that can result in cognitive disturbances, physical symptoms, and emotional lability. Up to 3.8 million American university athletes may sustain a concussion each year (Langlois, Rutland-Brown, & Wald, 2006). In New Zealand, a total of 5,556 sport-related concussion medical claims were filed between 2012 and 2016, comprising 28% of all concussion claims and costing NZD $34,421,704 in compensation, or $6,884,341 per year (King et al., 2019). Many athletes choose not to report their injury or seek treatment despite being aware of the symptoms and long-term risks of concussive damage (Leahy, Farrington, Whyte, & O'Connor, 2020; Meier et al., 2015), so these figures may only represent 70% of all sports-related concussions (LaRoche, Nelson, Connelly, Walter, & McCrea, 2016; Meehan, Mannix, O'Brien, & Collins, 2013).

The most common acute symptoms of concussion are headaches, dizziness, fatigue, irritability, and confusion (Daneshvar, Nowinski, McKee, & Cantu, 2011; McCrory et al., 2017). Neurocognitive deficits often include attention, information processing speed, memory, and executive functioning (Collins et al., 1999; Macciocchi, Barth, Alves, Rimel, & Jane, 1996; Macciocchi, Barth, Littlefield, & Cantu, 2001; McCrea et al., 2003). These clinical impairments can translate to functional difficulties with skill acquisition and performance (Van Vleet et al., 2016).

Researchers have often characterized skill acquisition as a process of three stages (DeKeyser, VanPatten, & Williams, 2007). In the first stage (declarative), an individual creates a step-by-step

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understanding of how to do something; in the second stage (procedural), they practice the skill and it becomes less declarative and more performative; when they reach the third stage (automatic), they can perform the skill effortlessly (Anderson et al., 2004; Taatgen, Huss, Dickison, & Anderson, 2008). This progression requires sustained attention to the task; memory for the declarative task instructions; rapid and coordinated visual and motor functioning; and executive control sufficient to monitor task performance, compare task performance to a performative model, and self-correct when errors are detected. Because they are continuously receiving performance feedback and integrating that feedback into their skill development, and as they are also highly trained athletes, university-level athletes likely operate largely within the procedural to automatic stages of skill acquisition.

The neurocognitive deficits commonly found immediately after concussion in university football players are among the most crucial to skill acquisition: problems with sustained auditory attention and visuomotor speed (Macciocchi et al., 1996), verbal learning and delayed recall deficits (Collins et al., 1999), and mild declines in processing speed, verbal fluency, cognitive flexibility (switching), and learning and memory (McCrea et al., 2003). Athletes with multiple concussions show more deficits in executive functioning and processing speed when compared to athletes with no prior history of concussions (Collins et al., 1999). Deficits in verbal learning and memory have been found to persist for at least 5 days (Collins et al., 1999), and to return to baseline after 7 days (McCrea et al., 2003).

Persistent post-concussive symptoms (experienced more than three months post-injury) are often estimated to occur in 10-15% of concussions, but estimates vary from 1.4-29.3%, depending on the diagnostic criteria used (Rabinowitz & Arnett, 2013; Rose, Fischer, & Heyer, 2015; Sterr, Herron, Hayward, & Montaldi, 2006). The most common cognitive deficits observed more than one year post-injury are in attention, memory, and processing speed (Dean & Sterr, 2013; Konrad et al., 2011; Sterr et al., 2006). Depression is also a common persistent post-concussion symptom that affects approximately 50% of concussed people in the first year post-injury (Barker-Collo et al., 2015; Bombardier et al., 2010).

In addition to these cognitive effects, emotional symptoms of concussion can also affect skill acquisition by reducing motivation and by directly decreasing cognitive functioning, potentially seen as lapses of memory or concentration. Depression can be caused or worsened in student athletes by being benched and feeling useless, poor academic performance because of persisting cognitive symptoms, lack of team support, and an uncertain return-to-play timeline (Chen, Johnston, Petrides, & Ptito, 2008; Kuehl, Snyder, Erickson, & McLeod, 2010). Post-concussive mood dysfunction may cause or exacerbate deficits in reaction time, processing speed, and visual memory post-injury (Bailey, Samples, Broshek, Freeman, & Barth, 2010; Kontos, Covassin, Elbin, & Parker, 2012). Furthermore, many other concussion symptoms overlap with symptoms of depression, which can make it hard to detect after an injury (Barker-Collo et al., 2015). As with neurocognitive deficits, depression can impede skill acquisition and performance, and may consequently affect the student athlete's daily functioning, including their academic performance (Hysenbegasi, Hass, & Rowland, 2005). Thus, it is important to assess depression when studying post-concussive neurocognitive deficits.

Risk factors for sport-related concussion include history of concussion (Guskiewicz et al., 2003; Lynall, Mauntel, Padua, & Mihalik, 2015; Macciocchi et al., 2001; McCrory et al., 2017; Nordström, Nordström, & Ekstrand, 2014), fatigue (Finnoff, Jelsing, & Smith, 2011), and pre-existing pathology or psychological distress such as depression or anxiety (Fann et al., 2002; Vassallo, Proctor-Weber, Lebowitz, Curtiss, & Vanderploeg, 2007). Fann and colleagues (2002) examined injury prevalence risks associated with psychiatric illness and found increased rates of concussion in individuals who had been treated in the past year (including medication and mental health services). Vassallo and colleagues (2007) found increased concussion rates in individuals diagnosed with depression, anxiety, and conduct disorders. Additionally, depression that presents or worsens after a concussion is associated with poorer outcome (van der Naalt et al., 2017). In this way, depression could act as both a risk factor and a symptom of concussion. Most research on risk factors of sustaining a concussion has focused on intrinsic pre-injury factors, while research on environmental or post-injury risk factors tends to examine the effects on recovery timelines and not prevalence.

An environmental factor that may affect an athlete's vulnerability to concussion is field elevation (above sea level).[i] Some researchers have found evidence for differences in concussion rates and recovery times among football players by elevation. Lynall and colleagues (2016) determined that the relative risk of concussion was 1.47 times higher for university athletes at the highest quartile of elevation, compared to those at the median elevation of 178 m (584 ft), and was 1.67 times higher than those at the lowest quartile. The athletes' recovery time was also longer when the elevation was higher than the median; 60.3% of athletes concussed below 178 m returned to full activity within six days, as opposed to 37% of athletes concussed above 178 m (Lynall, Kerr, Parr, Hackney, & Mihalik, 2016). Moderate elevation may cause the onset of mental and physical fatigue sooner than at sea level, leading to lapses in concentration and poorer self-protection and increasing the risk of injury. Elevation also could affect injury severity and duration by reducing the body's ability to use available oxygen or by slowing the healing process. Increased oxidative stress can cause cellular damage when unstable free radicals "steal" electrons from proteins and cells, causing DNA breakage and induced apoptosis, or programmed cell death (Askew, 2002; Bakonyi & Radak, 2004). At increased elevation, the oxygen concentration in the air is the same, but the decreased air pressure makes the transport of oxygen more difficult, therefore reducing the usability of the oxygen present (Askew, 2002). These hypoxic conditions interact with factors like reduced antioxidant activity at elevation and increased UV light in a closer and thinner atmosphere, and can cause the formation and increase the activity of free radicals (Askew, 2002; Bakonyi & Radak, 2004). In the presence of one stressor, the body's antioxidant defense system has a reserve of vitamins, enzymes, or other nutrients that can usually "sacrifice" their own electrons to prevent damage to other molecules, but when two or more stressors are present the defense system can become overwhelmed, and oxidative damage can occur (Askew, 2002). When exercising at moderate elevation, hypoxic damage may reduce cellular metabolism and cause or contribute to the aforementioned neurocognitive impairments after concussion.

In contrast, studies done at the high school level (Smith et al., 2013) and at the professional level (Myer et al., 2014) found that athletes sustain fewer concussions at moderate elevations, though they did not study recovery times. The researchers propose a “tight fit” theory to describe physiological mechanisms by which moderate- to high-elevation exposure could swell the brain to protect against concussions (Myer et al., 2014; Smith et al., 2013). Reduced usable oxygen at moderate elevation raises the athlete’s blood pressure (because extra force is needed to distribute the oxygen through the bloodstream at higher elevations), causing the cranial blood vessels to swell to fill the space between the brain and the skull. Jugular constriction prevents drainage and holds the blood in the cranium, keeping the brain engorged and firm. This swelling ostensibly limits inertial damage from “slosh,” which describes the collision of the semi-liquid brain into the skull due to sudden and rapid changes in acceleration/deceleration forces and the differential rotational speeds between the brain and skull (Gu, Kawoos, McCarron, & Chavko, 2017; Myer et al., 2014; Smith et al., 2013). Though it may seem contradictory, the “tight fit” theory may be compatible with Lynall and colleagues’ (2016) findings of more severe concussions at higher elevations. It is possible that the “tight fit” may reduce the overall incidence of concussion at elevation, but those who sustain concussions at higher elevations are still vulnerable to prolonged recoveries because of the effects of mild hypoxia.

1.1. Current study

The current study aims to contribute descriptively to the sparse literature on concussion at elevation by examining the longitudinal course of neuropsychological functioning in a sample of concussed and non-concussed football players over a season at moderate elevation. We hypothesized that concussed athletes would show more pre- to post-season declines in attention, processing speed, memory, and executive functioning, but not in estimated verbal IQ, than athletes who did not sustain concussions. We then posed research questions to 1) examine the relationship between concussion and depressive symptoms pre- and post-season, and 2) examine if depression is a risk factor for sustaining a concussion. Our results also serve as descriptive neuropsychological data of untreated concussions, since 80% of our concussed athletes did not report their injuries until the post-season assessment.

2. Methods

2.1. Participants

All participants were male student athletes aged 18 and older who played American football for a Division II university at moderate elevation (1966 m above sea level). Twenty-two athletes consented to participate and were administered a 40-minute neuropsychological test battery before the start of the 2016 college football season. Participants were only included if they completed both the pre-season and post-season assessments; no additional exclusion criteria were applied. Thirteen participants completed both assessments and the end-of-season questionnaire, and were included in analyses. The average participant age (N = 13) was 20.08 years old (SD = 2.40). Participants were almost evenly split between freshmen (first-year students, 30.8%), sophomores (second-year students, 30.8%), and juniors (third-year students, 38.4%). Seven (53.9%) played offensive positions, five (38.4%) played defensive positions, and one (7.7%) played on special teams as a kicker. Participants had been playing football for an average of 9.9 years (SD = 4.73). Eight (61.5%) participants reported having previously sustained concussions, and of those eight, three (37.5%) reported loss of consciousness.

Five of the 13 participants (38.5%) were believed to have sustained concussions during the course of the study, while eight (61.5%) did not. The only injury that was reported mid-season (and tested during the sub-acute phase) was caused by a motorcycle crash and was verified by the athletic trainer. The remaining four concussions were sustained during a game and reported only on the end-of-season self-report questionnaire, so those athletes were not tested during the acute or sub-acute phase. The most frequently cited reasons for not reporting the concussion when it occurred were: not thinking it was serious, not wanting to miss practice, and not wanting to disappoint the team. Three of the athletes played offensive positions (running back, tight end, and offensive lineman), and the fourth played a defensive position (line-backer). Two participants—the participant who sustained his concussion in a motorcycle crash, and another with no evidence of concussion—also completed the neuropsychological battery within a week of the concussion.

2.2. Procedure

We recruited football players from a pre-season team meeting. Players who agreed to participate scheduled a baseline neuropsychological assessment before contact practice began. All participants signed informed consent forms and HIPAA-compliant release forms allowing the athletic trainer to notify us if a participant sustained a concussion. Participants completed an athletic questionnaire that included demographic information and medical history. Neuropsychological assessments were completed individually in sound-proofed rooms and took 40 minutes to administer. If a participant sustained a concussion during the season, efforts were made to have the concussed participant and a non-concussed participant complete the battery again within 48 hours of the concussion, using alternate forms of the neuropsychological tests when possible to reduce the practice effects, as is standard for longitudinal research on neuropsychological functioning (Brandt & Benedict, 2001; Lezak, Howieson, & Loring, 2012). At the end of the season, participants again completed the neuropsychological test battery and an end-of-season questionnaire. Follow-up calls were made to participants who admitted to an unreported concussion to confirm the date and elevation at which it was sustained. Three concussions were sustained at the home elevation (1966 m, including the treated participant), one was sustained at a higher elevation (2076.3 m) and one was sustained at a lower elevation (871.7 m). At the time of the post-season evaluation, one concussed participant was tested six days post-injury, and the remaining four concussed participants were tested at the end of the season, between 26-93 days (m = 45.9) after their injury. One date of injury and one date of end-of-season assessment were estimated and are accurate within a week.

2.3. Tasks

The Hopkins Verbal Learning Test, Revised (HVLT-R) measures verbal learning and memory through a list of 12 semantically related words (Brandt, 1991; Brandt & Benedict, 2001). The HVLT-R includes three immediate recall trials (for a composite learning score), a delayed recall trial, and a recognition trial, with six alternate forms to minimize practice effects. Higher scores indicate better performances. Test-retest reliability has been found to be high for the learning and delayed recall trials: learning, r = .74; delayed recall, r = .66; recognition, r = .39 (Benedict, Schretlen, Groninger, & Brandt, 1998; Collins et al., 1999; McCrea et al., 2003; Rabinowitz & Arnett, 2013).

The Grooved Pegboard test (GP) measures fine motor skills and bilateral dexterity, and is reputed to detect neurological injury even when other tests cannot (Collins et al., 1999; Lafayette Instrument, 2014). This test is timed and performed using the dominant and then non-dominant hand, with faster times (lower numbers) indicating better performances. Its test-retest reliability has been found to range from r = .67-.86, and there is a practice effect associated with this test (Bornstein, Baker, & Douglass, 1987).

The Digit Span (DS) is part of the WAIS-IV and measures attention span and working memory by asking participants to repeat increasingly long strings of numbers both forward and backward (Collins et al., 1999; Wechsler, 2008). Higher total scores indicate better attention (DS-forward) and working memory (DS-backward). Since attention span is typically limited to an average of seven items (Miller, 1956), there is no significant practice effect is associated with this test. The digit span has been found to have an internal consistency of r = .93 across the normative sample of people aged 16-90 and an internal consistency of r = .91 for the normative sample of people aged 20-24. It has been found to have a test-retest reliability of r = .74 for the DS-forward and r = .69 for the DS-backward (Wechsler, 2008).

The Trail-Making Test (TMT) is a timed test with two parts that measure visual attention, psychomotor speed, and task switching (Reitan, 1958). Trail-Making Test A (TMTa) primarily measures psychomotor speed and visual scanning (Lovell & Solomon, 2011). Trail-Making Test B (TMTb) additionally measures cognitive flexibility and switching, which are aspects of executive functioning. Used together, these tests examine psychomotor speed, visual attention, and switching. Because the primary score for this test is completion time, lower scores indicate better performance. This test is considered reliable at r = .40-.60 (Ross et al., 2007), but it has been found to be vulnerable to practice effects, with times on the TMTb reduced by as many as four seconds (Lovell & Solomon, 2011).

The Controlled Oral Word Association Test (COWAT) measures phonemic verbal fluency (Benton & Hamsher, 1978). The COWAT is scored by adding the total number of correct words named that start with different letters over three trials (one letter per trial). Higher scores indicate better performances. Many concussion assessment batteries use this test, and it has shown adequate inter-rater reliability between r = .70-.80 (Abwender, Swan, Bowerman, & Connolly, 2001).

The North American Adult Reading Test, Revised (NAART-R) is used to estimate verbal intelligence, which is not thought to be affected by concussion (Blair & Spreen, 1989; Leininger, Gramling, Farrell, Kreutzer, & Peck, 1990; Sterr et al., 2006). The NAART-R is a list of 63 words with silent letters or unconventional pronunciations (debris, quadruped, sidereal), and higher numbers of words pronounced correctly indicates better performance. The NAART-R has been found to have an inter-rater reliability of r = .93 and to be correlated (r = .75) with the WAIS-R Vocabulary subtest (Uttl, 2002).

The Beck Depression Inventory, 2nd Edition (BDI-II) is a 21-item self-report measure of depressive symptoms (Beck, Steer, & Brown, 1996). Each symptom is rated on a 4-point scale that ranges from 0 to 3; total scores can range from 0 to 63, with higher scores indicating more depression symptoms. The BDI-II has shown an internal consistency of α = .92 and a test-retest reliability of r = .93 (Beck et al., 1996). The BDI-II is positively correlated (r = .71) with the Hamilton Psychiatric Rating Scale for Depression (Beck et al., 1996).

At the time of the baseline evaluation, participants completed a demographic and athletic questionnaire to assess their personal histories, including their football playing history, medical history (specifically past concussions with or without loss of consciousness, other brain injuries, and mental health diagnoses) and family history of neurodegenerative disease. At the end of the season, participants completed a questionnaire about concussions sustained that they did not report to their coaches or athletic trainers, which included a definition of a concussion and reasons why the athlete may not have reported the concussion. This questionnaire was adapted from La Roche and colleagues' (2016) study on rates of reported and unreported concussions.

2.4. Ethical considerations

This study received IRB approval from New Mexico Highlands University on 6 June 2016. All participants completed an informed consent form, as well as a HIPAA student athlete release form permitting athletic trainers to share information about the athlete's injuries with the researchers. No deception was involved.

2.5. Statistical approach

Participants (N = 13) who had completed both the baseline and end-of-season neuropsychological evaluations were included in the data analyses. Out of five concussed athletes, one athlete was diagnosed, removed from play, and treated, so we have excluded his data from group analyses to focus on the remaining four athletes who did not report their concussions and were not treated. We also ran analyses with all five concussed athletes included, and found almost identical results, so only analyses of the untreated athletes are reported here.

We analyzed the data in SPSS, and we primarily used repeated-measures ANOVAs and ANCOVAs (controlling for depressive symptoms, whose effect was determined by a t-test). The statistical tests for the hypothesis were one-tailed and the tests for the research questions were two-tailed. The assumption of equality of variance (Levene's test) was met for all subtests, but for the BDI-II it approached a violation at p = .063. The assumption of equality of covariance (Box's test) was met for all subtests. The assumptions of normality (assessed by the Shapiro-Wilk test with residuals) and of sphericity were met for all subtests. All results are reported at a 95% confidence interval.

Table 1: Pre-season to post-season changes in BDI-II scores of concussed participants

Concussed athlete	Pre-season BDI-II	Range	Days post-injury	BDI-II Increase	Post-season BDI-II	Range
A	1	Minimal	26	+14	15	Mild
B	3	Minimal	92	+10	13	Mild
C	20	Moderate	65	+1	21	Moderate
D	9	Minimal	42	0	9	Minimal
E (treated)	12	Minimal	60	+8	20	Moderate
Mean	9	Minimal	57	+6.6	15.6	Mild

Note: BDI-II=Beck Depression Inventory, 2nd Edition.

3. Results

3.1. Depressive symptoms in concussed & non-concussed participants

A *t*-test was used to examine whether concussed and non-concussed participants differed in baseline depressive symptoms, to test pre-injury depression as a risk factor for concussion. Participants who sustained a concussion in 2016 reported a higher average BDI-II score before the season (M = 9.0, SD = 7.6) than the participants who did not sustain a concussion (M = 5.7, SD = 2.9), but the between-group differences were not significant, $t(10) = -1.058$, $p = .315$. A repeated-measures ANOVA was then calculated using BDI-II score as the dependent variable and concussion status (concussed vs non-concussed) as the independent variable. A significant main effect was found for time, with an overall trend for increasing depressive symptoms, $F(1, 1) = 5.444$, $p = .040$. Additionally, a significant group (concussed vs non-concussed) by time interaction was found; the non-concussed group showed no change in depressive symptoms over time, whereas the concussed group showed a significant increase in depressive symptoms, $F(1, 1) = 6.335$, $p = .029$ (Figure 1). Because of this significant interaction, changes in BDI-II scores were included as a covariate in repeated measures ANCOVAs to examine the relationship between concussion status and performance on the other neuropsychological measures.

BDI-II scores of 0-13 points are considered indicative of "minimal" depression, scores of 14-19 points "mild" depression, scores of 20-28 points "moderate" depression, and scores over 29 points "severe." Three concussed participants who reported minimal depressive symptoms in the beginning of the season had entered the mild or moderate range post-concussion. The individual changes in BDI-II scores are shown in Table 1.

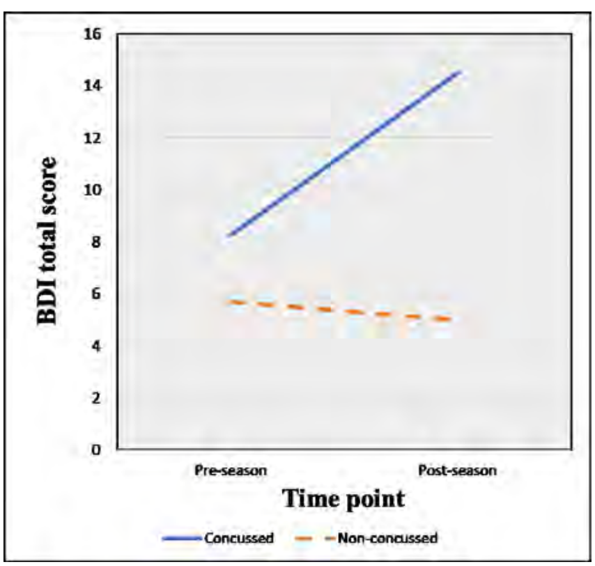

Figure 1: Pre-season to post-season change in BDI-II score by group

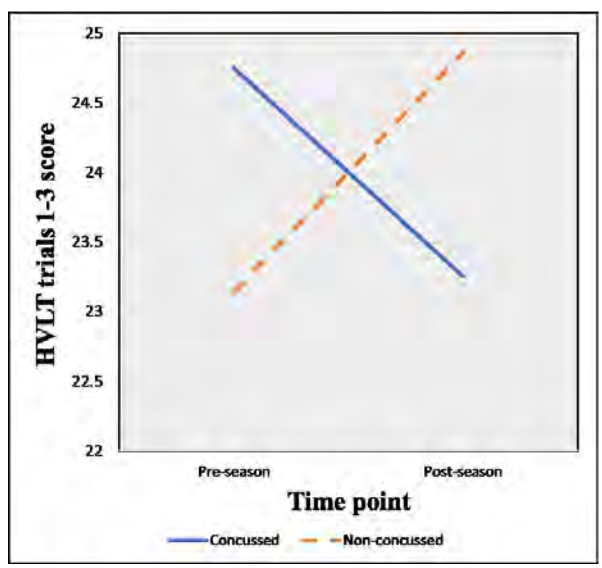

Figure 2: Pre-season to post-season change in HVLT Learning score by group

Table 2: Pre-season (T_1) to post-season (T_2) repeated-measures ANCOVAs for neuropsychological tests by concussion status, controlling for changes in BDI-II scores

Test	**T_1 (conc.)** *M (SD)*	**T_2 (conc.)** *M (SD)*	**T_1 (cont.)** *M (SD)*	**T_2 (cont.)** *M (SD)*	***F (df)***	***p***	**1-ß**
HVLT learning	24.75 (3.59)	23.25 (3.20)	23.14 (1.77)	24.86 (3.81)	6.54 (1, 8)	**.03 ****	.61
HVLT recall	9.25 (.50)	9.75 (1.89)	9.00 (1.16)	8.57 (1.99)	.00 (1, 8)	.99	.05
HVLT recog.	11.50 (.71)	12 (0)	11.80 (.45)	12 (0)	.64 (1, 8)	.89	.05
GP dom.	81.25 (15.31)	81.75 (9.78)	69.57 (10.85)	72.14 (9.35)	.20 (1, 8)	.67	.07
GP non-dom	87.00 (12.11)	96.50 (9.98)	78.14 (13.46)	81.71 (20.09)	.88 (1, 8)	.38	.13
COWAT	30.50 (6.86)	37.50 (3.11)	34.57 (5.47)	37.43 (7.61)	.29 (1, 8)	.61	.08
DS forward	6.75 (2.22)	7.75 (2.06)	6.57 (1.72)	7.00 (1.29)	.23 (1, 8)	.64	.07
DS back	7.00 (3.37)	6.50 (1.29)	5.33 (1.03)	6.83 (2.64)	.98 (1, 8)	.36	.14
TMTa	24.25 (7.93)	33.25 (5.38)	33.71 (8.50)	24.86 (5.27)	26.51 (1, 8)	**.001 ****	.99
TMTb	80.75 (23.17)	54.75 (6.19)	85.43 (54.89)	69.57 (23.84)	.29 (1, 8)	.65	.07
NAART-R total	26.75 (3.95)	26.50 (4.73)	19.29 (9.27)	20.71 (9.43)	1.88 (1, 8)	.21	.23
NAART-R FSIQ	101.09 (3.08)	100.75 (3.78)	95.26 (7.23)	96.43 (7.30)	1.92 (1, 8)	.20	.23

Note. T_1=pre-season; T_2=post-season; conc=concussed participants; cont.=non-concussed participants; 1–ß = power; BDI-II=Beck Depression Inventory, 2nd Edition; HVLT=Hopkins Verbal Learning Test; recog.=recognition; GP=Grooved Pegboard; dom. =dominant; DS=Digit Span; TMT=Trail-Making Test; COWAT=Controlled Oral Word Association Test; NAART=North American Adult Reading Test. ** denotes $p < .05$.

3.2. Short-term neuropsychological effects of concussions

Repeated-measures ANCOVAs (with change in depression as the covariate) were used to compare changes in neuropsychological test performance between the concussed and non-concussed groups. When controlling for depressive symptoms, significant group-by-time interactions were found for the HVLT learning recall trials and TMTa time. Total words recalled in the HVLT learning trials increased for non-concussed participants, but declined for participants who had sustained a concussion, F (1, 8) = 6.543, p = .034 (Figure 2). TMTa times decreased for the non-concussed participants, and increased for the participants who sustained concussions, F (1, 8) = 26.511, p = .001 (Figure 3). There were no significant group-by-time interactions in performance on the NAART-R, F (1, 8) = 1.882, p = .207, or the other neuropsychological tests. Results of all ANCOVAs are reported in Table 2.

3.3. Acute neuropsychological functioning comparison of a concussed vs non-concussed athlete

For illustrative purposes, Figure 4 shows the difference in performance on all neuropsychological tests between the concussed athlete and a non-concussed athlete. Because of the small sample size, these data were not subjected to standard statistical tests, and should instead be interpreted as a descriptive comparison of a post-concussive neuropsychological recovery trajectory to healthy neuropsychological functioning. A closed triangle represents a complete return to baseline after post-concussive impairment.

The athlete who reported his concussion during the season and a control participant without any suspected concussion were administered the neuropsychological battery after the concussion was reported (six days post-concussion). The concussion was sustained at 1966 m during a motorcycle crash, not a game or practice.

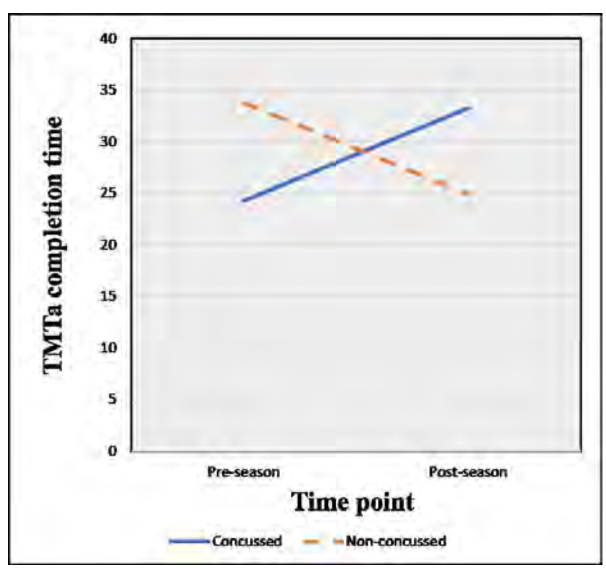

Figure 3: Pre-season to post-season change in TMTa score by group

Declines in functioning post-injury were seen on the HVLT delayed recall, HVLT learning, DS-backward, and DS-forward, with an apparently incomplete recovery by the end of the season. The concussed athlete showed initial impairment after the concussion and then a return to baseline (or better) on the HVLT recognition, COWAT, GP, TMTa, and TMTb by the end of the season. Consistent with the results of the ANCOVAs (comparing neuropsychological functioning of the undiagnosed vs non-concussed athletes), the diagnosed athlete demonstrated an increase in reported BDI-II symptoms and a decline in performance on the HVLT learning trial at the post-season assessment when compared to the control athlete.

4. Discussion

This study intended to examine the neuropsychological consequences of concussions in university football players at moderate elevation of 1966 m (6,450 ft), but our results actually appear to reflect the effects of not seeking treatment on the course of recovery. All five football players who sustained concussions[ii] during the season showed significant declines by the end of the season than those without concussion on measures of processing speed and verbal learning (though the individual with the diagnosed concussion was not included in the neurocognitive statistical analyses reported). The specific domains of processing speed and verbal learning are consistent with other researchers' findings of concussed and subconcussed athletes (Collins et al., 1999; Fann, Uomoto, & Katon, 2001; McAllister et al., 2012; McCrea et al., 2003; Talavage et al., 2014), but the duration of injury is not. Because changes in depression symptoms were controlled for, the declines in neuropsychological functioning cannot be explained by depression. Additionally, our data do not support depression as a risk factor for concussion.

4.1. Selection & interpretation of data

The neuropsychological scores of the four athletes who reported a concussion in the end-of-season questionnaire were examined, and in all four cases demonstrated impairments consistent with concussion. We have no reason to believe any of the concussions were falsely reported, as false reports of sports-related concussion are rare because the athletes would have nothing to gain (especially at the end of the season). Very little literature exists regarding false reporting of sport-related concussion by athletes, though some research has studied over-reporting of concussion symptoms in military personnel (Armistead-Jehle et al., 2018; Cooper, Nelson, Armistead-Jehle, & Bowles, 2011; L. Miller, 2001) or those involved in litigation (Silver, 2012; Suhr, Tranel, Wefel, & Barrash, 1997), who have more external motivations to report or exaggerate symptoms (benefits, time off, or compensation) than university athletes. Even if our concussed athletes did not meet the clinical definition of concussion, they still showed more deficits than non-concussed or subconcussed athletes post-season (J. R. Miller, Adamson, Pink, & Sweet, 2007; Moore, Lepine, & Ellemberg, 2017), supporting their self-diagnosis of concussion.

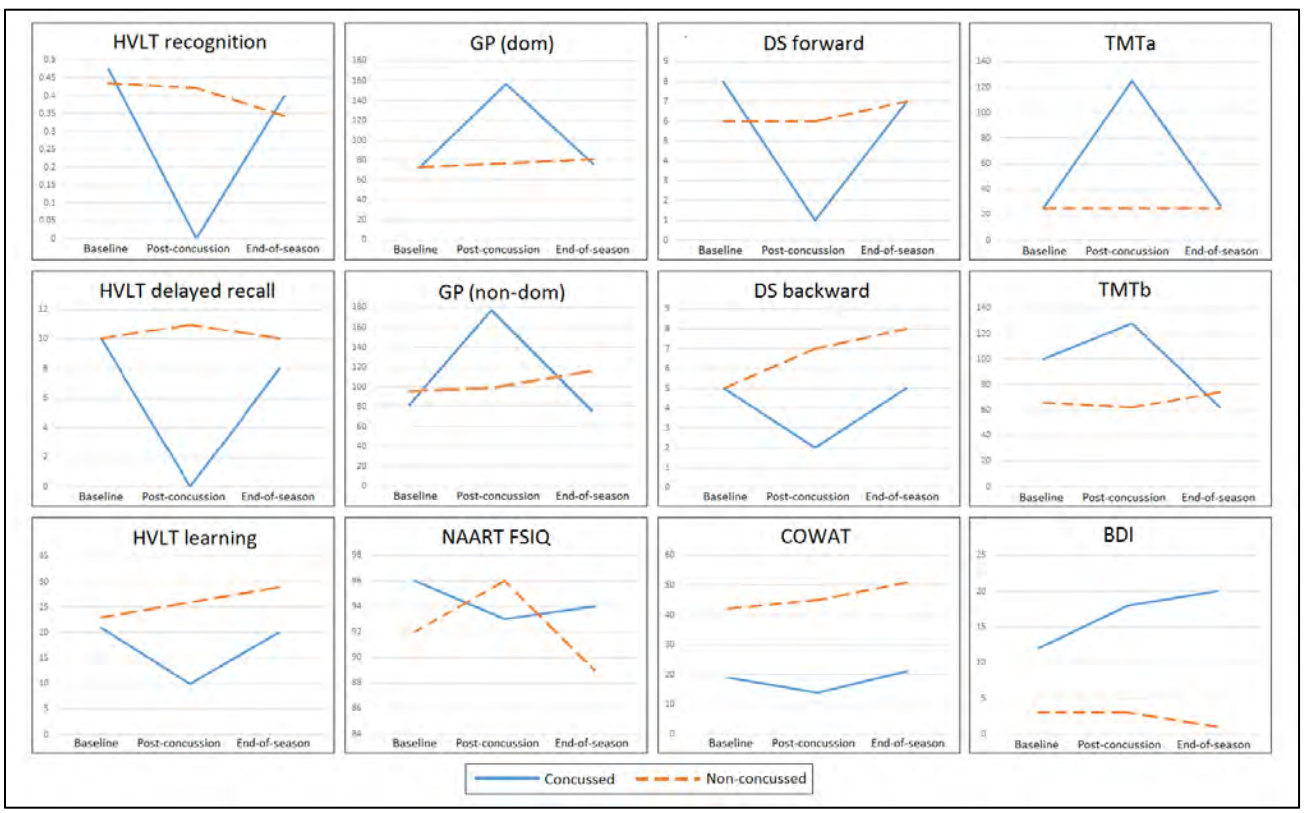

Figure 4: Comparison between concussed participant (in blue) and non-concussed participant (in red) mid-season

Our finding of a higher proportion of initially unreported (than reported) concussions is consistent with Meier and colleagues' (2015) conclusion that athletes are more likely to report symptoms in a confidential setting that is not connected to the athletic program. In a study on Irish amateur athletes, Leahy and colleagues (2020) reported that, of athlete respondents who believed they had sustained a concussion, 27.8% did not seek treatment, and 64% continued to play while symptomatic. Additionally, while 95% of the athletes self-reported understanding the serious nature of concussive damage, 48% of respondents said they would still hide a concussion during an important match (Leahy et al., 2020). La Roche and colleagues (2016) found that 29.4% of their sample of athletes did not report a concussion, and that the most common reasons were not thinking it was serious and not wanting to lose playing time, which is consistent with our results. Meehan and colleagues (2013) similarly found that 30.5% of athletes concussed during the study had previously sustained a untreated concussion. Our non-treatment-seeking finding of 80% is higher than most reports in the literature (rarely estimated over 50%), but we were not methodologically equipped to study reporting rates accurately.

4.2. Unreported/untreated concussions & consequences of RHIs

Current literature suggests that over 80% of concussions should resolve 7-14 days post-concussion (Karr, Areshenkoff, & Garcia-Barrera, 2014; McCrory et al., 2017). The most likely reason that the concussed athletes in this study did not demonstrate a complete recovery is because they did not report their injuries or seek treatment. Time to treatment is a critical determinant of recovery (Eagle, Puligilla, et al., 2020; Kontos et al., 2020), and continued exposure to concussive damage in an already neurologically weakened state is associated with many additional risks, including increased vulnerability from continued head impacts or other injury (Eagle, Kontos, et al., 2020; Stemper et al., 2019; Talavage et al., 2014), prolonged recovery from concussion (Sterr et al., 2006), and increased risk of neurodegenerative disorders like Alzheimer's disease or chronic traumatic encephalopathy later in life (Finkbeiner, Max, Longman, & Debert, 2016; Guo et al., 2000; McAllister & McCrea, 2017; Mouzon et al., 2018), the last of which is especially relevant to individuals with a history of multiple concussions (Guskiewicz et al., 2005). Finally, an athlete who does not remove themself from play is also at increased risk of receiving a second and fatal impact, especially in the first 10 days post-concussion, though this is rare (Bey & Ostick, 2009).

The absence of a diagnosed or suspected concussion (due to observable behavioral or neuropsychological signs) does not mean that no neurological damage has occurred. Subconcussive injury can happen when athletes experience enough repetitive head impacts (RHIs) at forces not severe enough to cause a concussion or gross neurocognitive deficits (J. R. Miller et al., 2007; Moore et al., 2017). Subconcussive damage has mainly been detected as white matter damage (Bazarian et al., 2014; Gu et al., 2017; McAllister et al., 2014; Moore et al., 2017), neurometabolic changes (Bailes, Petraglia, Omalu, Nauman, & Talavage, 2013; Bari et al., 2019; Hunter, Branch, & Lipton, 2019), and alterations to electrophysiological activity or communication networks (Abbas et al., 2015; Moore et al., 2017; Pearce, 2016), though some researchers have found subtle neurocognitive deficits in asymptomatic athletes after a season (McAllister et al., 2012; Talavage et al., 2014).

RHIs may increase the risk of sustaining a concussion by lowering the threshold of force needed to cause injury or induce symptoms (Caccese et al., 2018; Stemper et al., 2019). Stemper and colleagues (2019) found a significant increase in RHIs in 72% of concussed athletes in the days leading up to concussion, which was often sustained from impacts with low concussive probabilities; over half were caused by forces thought to have a <1% risk of injury. Beckwith and colleagues (2013) found that more head impacts were associated with a delayed diagnosis of concussion, while those diagnosed immediately had experienced impacts of higher forces. Because the concussed athletes in this study did not report their injury (and therefore were not removed from play, diagnosed, and treated), they were then exposed to further impacts and subconcussive brain trauma that may have exacerbated their symptoms and prolonged their recovery.[iii]

Though our research focuses on athletes, unreported concussions are common in the general population. Factors linked with not seeking or receiving care include older age, an injury sustained in sport or at home, being a current smoker, and not being an immigrant (Gordon, 2020; Kiefer et al., 2015). While Gordon (2020) did not find any effects for gender, race, or income, he found that 21% of his respondents did not seek treatment in the first 48 hours, though he cites estimates that are higher. Hesitance to report concussion or seek treatment is also prevalent in American military personnel, where almost 50% may not seek care, mainly because they do not think the injury is serious or are worried about how it will affect their career (Escolas, Luton, Ferdosi, Chavez, & Engel, 2020).

4.3. Neuropsychological sequelae of untreated concussions & RHIs

The concussed athletes demonstrated persistent post-concussive neuropsychological effects in domains that are central to all three stages of skill acquisition, including poorer verbal learning and slowed processing speed (as well as increased depression) when compared to the non-concussed athletes at the end of the season. On the HVLT, the untreated athletes learned 1.5 fewer words at the end of the season than they had learned pre-season, whereas non-concussed athletes learned 1.8 more words than they had at baseline, likely due to a practice effect. Time needed to complete the TMTa for the untreated group increased by an average of 9 seconds, while the time of the non-concussed group dropped by an average of 9 seconds. These deficits in processing speed and verbal learning remained even when controlling for increased depression, suggesting that the cognitive declines were not caused solely by depressive symptoms. As predicted, we saw no difference in estimated verbal IQ, which is consistent with vocabulary being a relatively stable domain that is not known to be affected by concussive damage (King & Kirwilliam, 2011; Leininger et al., 1990; Sterr et al., 2006). There is a statistical possibility that, due to the low power, accepting the null hypothesis could be a type II error (false negative), but the probability of this is low, considering the existing research.

We can see from the comparison of the treated athlete to the non-concussed athlete that most neuropsychological domains showed damage immediately post-injury, and while most of these declines did resolve by the end of the season, the isolated deficits that persisted are comparable to those seen in the untreated athletes. Both the treated and untreated athletes in this study showed impairments in verbal learning and memory on the HVLT immediate recall trials. Only the untreated athletes showed post-season processing speed deficits on the TMTa, whereas the treated athlete showed initial impairment followed by a return to baseline. The treated athlete, however, did not show a return to baseline on the TMTb, demonstrating impaired cognitive flexibility not seen in the untreated group.

Though we did not examine head impact exposure, several studies on contact athletes who were and were not formally diagnosed with concussion have found similar short-term neuropsychological deficits (1-3 months post-injury). Verbal learning and memory and switching deficits are common after RHI and sport-related concussion (Collins et al., 1999; McAllister et al., 2012; McCrea et al., 2003; Talavage et al., 2014). Talavage and colleagues (2014) studied functional (not clinical) impairment on verbal and visual memory tasks in RHIs, and estimated that at least 17% of contact athletes who have not been diagnosed with concussion still experience neurocognitive impairments, mainly in visual and verbal working memory. McAllister and colleagues (2012) compared RHIs in contact and non-contact athletes and found poorer post-season performance by the contact athletes on the CVLT (a similar measure of verbal learning and memory), the TMTb, and a measure of reaction time. McCuddy and colleagues (2018) reported that depressive symptoms were correlated with significant changes to functional connectivity at one month post-concussion, specifically between areas involved in attention and default activity in a resting state. Their finding suggests that compensatory neurological alterations associated with attention and depression may persist for a month or more, despite concussion symptoms resolving within 1-2 weeks for a majority of concussed individuals (Karr et al., 2014; McCrory et al., 2017).

Some neuropsychological domains may be especially vulnerable to chronic damage from RHIs and concussive damage, especially if the athlete did not seek treatment. The processing speed deficit seen on the TMTa in the untreated players is somewhat consistent with findings of persistent deficits in information processing speed and working memory in a non-treatment-seeking population at least one year post-concussion, when compared to non-concussed controls (Dean & Sterr, 2013). Moore and colleagues (2017) found that athletes who were concussed at least 11 months before testing remembered significantly fewer words on the HVLT delayed recall trial than the subconcussed athletes, who in turn remembered significantly fewer words than the non-contact athletes. Verbal memory deficits and mood dysfunction were also seen by Lepage and colleagues (2019), who were investigating the long-term effects of RHIs on limbic structure volume in retired professional football players and controls, though the concussion history of the players was not specified.

4.4. Concussion and depression

The group-by-time interaction between depressive symptoms and concussion that we found supports depression as a serious and often persistent symptom of concussion (Chen et al., 2008; Konrad et al., 2011; Kontos et al., 2012; Lavoie et al., 2017). While the non-concussed athletes experienced no significant change in depression symptoms over the season, all five athletes with concussion reported a statistically significant increase of almost seven points, on average, in their BDI-II scores. In addition, three out of the five concussed athletes reported a clinically significant increase in the severity of their depression from their baseline to the end of the season (Table 1). These findings suggest that concussed athletes do experience a greater increase in depressive symptoms over non-concussed athletes, and people with untreated concussion may experience higher rates of post-concussive depression. There could be reasons unrelated to the concussion that the depression scores of these athletes increased (e.g., interpersonal stress, increased academic workload), however, they do not explain why the change in depression scores was more pronounced in concussed participants than in non-concussed participants.

Our data do not support others' findings of pre-existing psychological distress as a risk factor for concussion (Fann et al., 2002; McCauley, Boake, Levin, Contant, & Song, 2001; Vassallo et al., 2007), but our non-significant finding could be a false negative (type II error) due to our small sample size.

Treating an individual's post-concussive depression with medication or therapy can improve their injury outcome. Fann and colleagues (2001) conducted an 8-week pharmacological intervention in patients with depression 3-24 months post-mTBI, after which the patients' neuropsychological performances improved significantly in many domains, including completion times on both the TMTa and the TMTb. They concluded that cognitive deficits (such as verbal memory, psychomotor speed, and cognitive flexibility) and depressive symptoms seen in patients from 3-24 months after mTBI can be improved with depression treatment.

4.5. Contributions to elevation research

Though the likely explanation for our findings of persistent neuropsychological deficits among concussed student athletes is that the concussions were untreated, they should still be considered through the lens of the elevation at which the data were collected. Our study did not directly investigate elevation as a risk factor for concussion incidence or prolonged recovery, but our data of incomplete recovery in all five athletes suggest the need for more methodologically rigorous research into the role of elevation in concussion etiology and management. The three studies on concussion at elevation mentioned above (Lynall et al., 2016; Myer et al., 2014; Smith et al., 2013) were criticized for several methodological flaws, mainly the use of less than 200 m (550-650 ft) as the median between "high" and "low" elevation conditions; physiological changes are not seen below the 2200 m (7,000 ft) threshold accepted as "high elevation" by physiologists (Smoliga & Zavorsky, 2017; Zavorsky, 2016). Furthermore, the degree of elevation-induced swelling required to cause the "tight fit" only occurs above 4000 m (13,000 ft), and only in fewer than 4% of mountain climbers, an already small subset of the general population (Smoliga & Zavorsky, 2017; Zavorsky, 2014). A meta-analysis of the three studies (Zavorsky & Smoliga, 2016) found the risk of concussion to be equivalent in the low (0-200 m) and high (200-300 m) conditions, but the statistical model used and the selection and interpretation of the data were considered questionable (Bailes & Smith, 2017; D. M. Bailey et al., 2017; Myer, Schneider, & Khoury, 2017; Zavorsky & Smoliga, 2017). In addition, the meta-analysis only examined elevation as a risk factor for sustaining a concussion, and did not address the effect elevation may have on recovery time.

Other researchers have continued to study elevation's influence on concussion prevalence and recovery in athletes. Bogar and Schatz (2019) compared NFL concussion rates of the Denver Broncos (whose "mile high" playing field is the highest in the NFL at 1600 m) to the concussion rates of their three lower-elevation divisional rivals (who train at elevations of -6.4 m, 16 m, and 79 m), but they found no significant differences in the concussion rates. Connolly and colleagues (2018) also studied NFL concussion rates using less than 200 m (644 ft) as the elevation cut-off, and found lower rates of concussion at higher elevations in athletes from teams that train at the higher elevations, but not in athletes from teams who train at lower elevations when they travel to higher elevations. Adams and colleagues (2018) examined if hockey players missed more games (a marker of concussion severity) if their concussion was sustained over 300 m (1000 ft). They similarly determined that athletes who are based at higher elevations sustain fewer concussions when they travel to lower elevations, and that athletes missed fewer games from concussion when they trained at higher elevation, whether they were home or away (Adams et al., 2018).

These studies (Adams et al., 2018; Connolly et al., 2018) attribute this protective effect of elevation to acute and long-term adaptations made by athletes who train at higher elevations, not just an effect of a "theoretically protective physiologic cerebral edema." Adaptation is necessary for skill acquisition because it enables an individual to understand and execute their action capabilities, or the ability to perform common and familiar actions (like sitting down or stepping over something); subtle neurocognitive deficits may interfere with the ability to compensate for small everyday changes to these frequent actions, or with the process of re-integrating an individual's physical senses (such as proprioception or making perceptual judgments) into motor planning (Hirose & Nishio, 2001). Failure to make these dynamic adaptations could result in re-injury. Physiologic adaptation to a moderate elevation supports the "tight fit" theory of fewer concussions at higher elevations (Connolly et al., 2018), but the finding of fewer games missed at higher elevation (Adams et al., 2018) is not consistent with Lynall and colleagues' (2016) findings of longer recovery time for concussions sustained at higher elevation. At this point, it is unclear how or to what degree an adaptation to performing at moderate elevation would influence an athlete's post-concussion recovery.

Hypoxic stress is associated with acute neuropsychological impairment; concussions may produce persistent but subtle deficits in function that only emerge under stress or further injury, even when that individual appears to have recovered. Deficits in memory and vigilance (a type of attention) were seen in concussed participants in a study by Ewing and colleagues (1980), in which ten participants who had recovered from a recent concussion and ten un-injured controls were asked to perform neuropsychological tests in conditions to simulate a hypoxic atmosphere of 3810 m (12,500 ft). Those in the control group scored about 90% correct on the vigilance task at 10 minutes, 20 minutes, and 30 minutes, while the concussion group scored about 85% correct at 10 minutes and 20 minutes, but dropped to 80% correct at 30 minutes. Manderino (2020) also studied the effect of hypoxia as a stressor on cognitive performance (up to 75 minutes exposure) in individuals who had recovered from a concussion and in controls with no concussion history. While control participants experienced improvements in attention scores at the simulated elevation of 4267 m (14,000 ft), the concussed participants did not, though they did exhibit an acute increase in negative affective changes. She attributed this improvement to an adaptive benefit of stress not experienced by those with a history of concussion. This chronic stress-induced vulnerability may be due to the effects of decreased oxygen use (at simulated elevation), but other unmeasured risk factors or stressors (like athletic exertion) might also be involved.

Elevation remains a controversial topic because research done in the 200-300 m "high" elevation condition of these studies is not generalizable to physiologically moderate elevations above 2000 m, and because the physiological explanation of the "tight fit" theory is based on an adaptation that protects woodpeckers and big-horned sheep from repetitive head impacts, and may not be generalizable to humans (Bailey et al., 2017). It is also possible that the effects of mild hypoxia at moderate elevation contributed to lowering the threshold for concussive or subconcussive damage, though it is unclear why one athlete over another would be more vulnerable to chronic damage or neurocognitive symptoms at moderate elevation. The mildly hypoxic effect of moderate elevation could also partially explain why the single treated athlete had still not fully recovered by the end of the season. Our results suggest that return-to-play guidelines at moderate and higher elevations should be more conservative, and athletes should be monitored closely to ensure they fully return to baseline performance before returning to play.

4.6. Limitations, strengths, & implications for future research

This study had several limitations, including a 40% attrition rate, low power due to a small sample size, and reliance on self-report data for many of the concussions. Our information regarding treatment of the athletes post-concussion was incomplete, specifically in concussion management by the athletic training staff and how quickly the concussed athletes returned to play. These factors may have affected our results by limiting our ability to evaluate the athletes immediately after their concussion and potentially causing type II errors in our analysis. In addition, though our initial study design included a sea-level team for comparison, we were unable to establish data collection at a second location, and therefore were unable to compare prevalence rates and recovery times between elevations.

One strength of this study is the use of an end-of-season questionnaire to identify athletes who likely sustained a concussion but did not report it, resulting in a focus on a different population than intended (though without medical evaluations we cannot say with certainty that they were concussed). This study provided some insight into the field of non-treatment-seeking athletes, which is a difficult group to study intentionally. Another strength is the use of the BDI-II to control for psychological symptoms commonly seen post-concussion that can affect cognitive functioning. Because of the inclusion of the BDI-II, the end-of-season deficits observed in the concussed athletes cannot be attributed to depressive symptoms.

We find elevation a compelling area for future study; future researchers should study larger cohorts of athletes with diagnosed and treated concussions, playing at moderate elevation and sea-level schools concurrently to assess the role elevation plays in concussion risk, severity, and recovery, and to determine the parameters of its physiological effects. Future research can also prospectively focus on comparing athletes with untreated vs treated concussions, based on a similar end-of-season screening.

Our findings also raise the possibility that an early therapeutic or pharmacological intervention in people whose depression followed the concussion may improve the injury outcome, or at least alleviate the depression to treat the other symptoms more effectively (Fann et al., 2001). Objective measures of somatic and psychological symptoms are needed to determine post-concussive damage to quality-of-life factors. A self-report symptom app might encourage reporting of symptoms, and would enable researchers the ability to schedule reminders and increase the number of assessments.

4.7. Conclusions

If an athlete does not remove themself from play after a suspected concussion, the athlete's brain remains exposed to repetitive head impacts and does not have an opportunity to heal, potentially leading to longer recovery times. The concussed athletes in this study showed persistent and clinically relevant changes on neurocognitive and depression symptoms at the end of the season, outside of the expected 7-10 day recovery timeline for treated concussions without complications (Karr et al., 2014; McCrory et al., 2017). These persistent deficits can interfere with skill acquisition and the ability to protect oneself post-injury/from re-injury.

Conflict of Interest

Neither author has any financial or institutional conflict of interests to declare. This study received no funding and was conducted through New Mexico Highlands University.

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[i] The terms "altitude" and "elevation" are used equivalently in this paper. Although other papers published in this area use the term "altitude" to describe a field's position above sea level, elevation is a slightly more accurate description. "Altitude" refers to the relative height of an object or person suspended above the ground (usually temporarily), whereas "elevation" refers to the height the ground is positioned above sea level.

[ii] Though they should be considered "potential" concussions because of their undiagnosed nature, they will be referred to as concussions in this study.

[iii] When interpreting research on subconcussion, it is important to note that while most athletes who do not report their concussion will experience further subconcussive injury/RHIs, not all athletes who experience subconcussive injury/RHIs have sustained an unreported concussion (although an unknown number have).