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Football-induced fatigue in hypoxia impairs repeated sprint ability and perceptual-cognitive skills

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ABSTRACT

Purpose: Investigate football-induced fatigue during hypoxia on RS and perceptual-cognitive skills.

Methods: Ten semi-professional footballers underwent a control session (0-m) to quantify RS in a non-fatigued state; and three hypoxia sessions (0-m;1500-m;3000-m) examining RS and perceptual-cognitive skills for a given physical workload. The mean number of correct responses (%) for anticipation and decision-making accuracy were obtained at the 30-min mark of each half. HR, TC, RPE and %O_2sat were measured during warm-up, football-induced fatigue and RS test.

Results: HR, RPE and %O2sat were different between conditions (ES=0.44-6.13). RS were affected by football-induced fatigue for DC (4.8%;ES=0.68) and AV (5.5%;ES=0.79). In hypoxia, a 6.5% was found for DC, 6.3% for AV and 3.1% for PV at 1500-m compared to 0-m (P<0.05). Further significant changes of 12.8% DC, 12.8% AV and 6.2% PV (P<0.0005) were found at 3000-m compared to 0-m. More pronounced declines in perceptual-cognitive skills were found as altitude increased (5.0-12.5%;ES=1.17-2.41) and between halves (5.3-6.7%).

Conclusion: The data demonstrates the RS test was sensitive to fatigue/hypoxia for a given physical load. Simulated matches in hypoxia revealed larger decreases, in RS and perceptual-cognitive skills, highlighting the need for optimal acclimatisation strategies, including physical and technical preparation, prior to playing at altitude.

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KEYWORDS
Altitude; soccer; repeated accelerations; decision making; anticipation

Introduction

Football is highly dependent on a myriad of factors (D'Hooghe 2013). Match analysis reveals elite football players typically cover 9–14 km during a game with high-intensity running accounting for 5–15% of match-play (Bangsbo et al. 2006; Faude et al. 2012). Repeated high-intensity actions are typically related to important phases of play (Nakamura et al. 2017), with straight sprinting found to be the most frequent movement in goal situations (Faude et al. 2012). More recently some studies have questioned the occurrence of repeated-sprint bouts during matches showing that only a few sequences happen throughout a match (Nakamura et al. 2017). However, the ability to repeatedly undertake maximal sprints with limited recovery and perceptual skills, more specifically being able to accurately anticipate and making the correct decisions are crucial to expert performance in football (Casanova et al. 2013). Both factors help determine the outcome of a situation and the ability of an individual to adapt in a dynamic environment will aid him to excel during a football match (Ando et al. 2013).

Because of geographic location, many teams are confronted with playing games at varying altitudes (Bärtsch et al. 2008; D'Hooghe 2013; Girard et al. 2013). The environmental impact of hypoxia on physiological and perceptual-cognitive performance is an important consideration for practitioners and policy makers (Girard et al. 2013; Aldous et al. 2016). Therefore, FIFA updated its current body of knowledge related to football performance at altitude and reached new guidelines with recommended exposure times for teams travelling to play at varying altitudes (D'Hooghe 2013). Evidence indicates that hypoxia adversely impacts performance variables related to football. During matches played at low altitudes, decrements of 3 % at 1200-m (Nassis 2013) and 9% at 1600-m (Garvican et al. 2014) in total distance covered are elicited. However, using match running performance measures in isolation to observe hypoxia related changes could be problematic as football is a self-paced sub-maximal sport with players only taxing their full physiological capacity during selected periods of match-play (Paul et al. 2015). Considering match related parameters can vary by 20–50% from game to game (Taylor and Rollo 2014) it is difficult to attribute the findings due to hypoxia to a single factor (e.g. tactics, opposition, score line; Aldous et al. 2016; Brocherie et al. 2017).

Cognitive function is an important determinant of performance in football and has been found to be impaired when players are physically and mentally fatigued (Smith et al. 2016). The negative impacts of fatigue on performance

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are well established and have been attributed to the inability numerous specific perceptual-cognitive abilities (Alfonso et al. 2012), such as attentional focus (Boksem et al. 2005), reaction time, accuracy and attentional visual cues (Boksem et al. 2006). It has also been suggested that hypoxia causes impaired cognitive function because of underlying mechanisms related to several biological processes (Ando et al. 2013). However, it remains unclear how physical fatigue under hypoxia affects perceptual-cognitive function specific to football.

Therefore, to gain a better understanding of the acute effects of hypoxia on football performance, controlled laboratory-based simulations replicating match demands have been developed (Drust et al. 2000; Aldous et al. 2014). Using a motorised treadmill increases the validity of measurements (Thatcher and Batterham 2004) and helps determine the physiological and perceptual-cognitive responses in football for a given physical load at hypoxia. The development of fatigue is associated with the inability to maintain RS performance (Galvin et al. 2013) and is markedly reduced in the second half of a match (Mohr et al. 2005; Armatas et al. 2007). Fatigue leads to more mistakes being made and more goals being scored in the final 15-min of a match during each half (Armatas et al. 2007). It also negatively impacts perceptual-cognitive skills (Royal et al. 2006). Changes in RS performance and perceptual-cognitive skills because of acute hypoxia exposure could further explain the increase in goals scored in the latter stages of each half.

Research has previously examined the relationship between fatigue and/or hypoxia on football performance. A review conducted by Girard et al. (2017) concluded that RS performance showed performance decrements when conducted at altitude due to multiple complex mechanisms. However, the relationship between fatigue and hypoxia on perceptual-cognitive skills related to football is unclear and unknown. These components of performance can differentiate players when compared to physical and physiological factors (Williams and Reilly 2000; Roca et al. 2013). Perceptual-cognitive skills have been shown to interact with one another during actual performance as a function of the unique constraints of the game (Roca et al. 2013). Therefore, integrating perceptual-cognitive skills during the last 15-min of each half and examining RS performance through an appropriate football related RS test (Bangsbo et al. 2006) at the end of a 90-min football simulation will provide more information on changes at varying degrees of hypoxia for a given exertion rate. This is particularly important as 1 to 3-s of explosive bursts involving rapid accelerations are common during match-play (Akenhead et al. 2013). It can help provide further information that can be pivotal in the strategic development of future research to minimise acute hypoxic effects.

To certify that the simulation tasks applied in this study effectively measure and capture perceptual-cognitive skills and that the RS protocol is able to detect establish expected trends during hypoxia and/or fatigue, it is important to establish the actual magnitude of change. Therefore, this study aimed to: (1) examine the effect of fatigue, following a laboratory-based football match simulation, and varying degrees of hypoxia on a football-specific RS performance (10 × 3-s sprints with 30-s recovery) test and (2) investigate the physiological and perceptual-cognitive skill responses in varying degrees of hypoxia during a laboratory-based simulated football.

Materials and methods

Subjects

Ten male, semi-professional football players were recruited for the study [age (mean ± SD) 21 ± 2 yr, peak oxygen uptake ($\dot{V}O_2$ peak) 63.2 ± 3.9 mL kg min^{-1}, stature 1.8 ± 0.6 m, body mass 75.5 ± 6.2 kg, body fat 13.7 ± 4.3%, waking and habitual retiring times 07:58 ± 00:50 h:min and 23:51 ± 00:25 h:min]. All players were members of both the University Men's football team and a semi-professional team. Players trained two to three times per week and played one to two 90-min matches per week. Inclusion criteria required previous football experience and a $\dot{V}O_2$ peak >55 mL·kg·min^{-1}. All conditions were double blinded and counterbalanced in order of administration to minimise and statistically distribute any learning effects. All sessions were conducted at the same time-of-day to eliminate any potential circadian influence on exercise performance. All players gave their written informed consent. The study was approved by the Human Ethics Committee of Liverpool John Moores University and conformed to the Helsinki Declaration.

Design

All sessions took place under standard laboratory conditions (lighting, room temperature, humidity and barometric pressure were 200–250 lux, 20.0 ± 0.8°C, 42.8 ± 9.9%, and 758.6 ± 7.9 mmHg). Prior to the main experiment, each player completed three familiarisation sessions separated by three days so that RS performance demonstrated a plateau effect. The overall coefficient of variation and 95% ratio limits of agreement for RS test were lower than 5 % and 10%, respectively. To ensure players were able to familiarise themselves with the perceptual-cognitive tasks, each participant received four random practice video clips during each of the three familiarisation sessions. They were required to provide information regarding What decision the players made or were about to make at video occlusion?' and 'What the player in possession was going to do?' Thereafter, each participant completed four experimental sessions seven days apart, in a counterbalanced design to minimise any learning or order effects. All players performed a RS test after a 5-min warm-up at normobaric normoxia (0-m) in a non-fatigued state; and three further sessions at varying degrees of normobaric hypoxia (FiO_2 = 20.9, 17.7 and 14.8%, effectively 0, 1500 and 3000-m altitude above sea level hereafter referenced to in 'm') in a hypoxic chamber creating a normobaric, hypoxic environment (TIS Services UK, Medstead, UK). A schematic representation of the research design can be found in Figure 1.

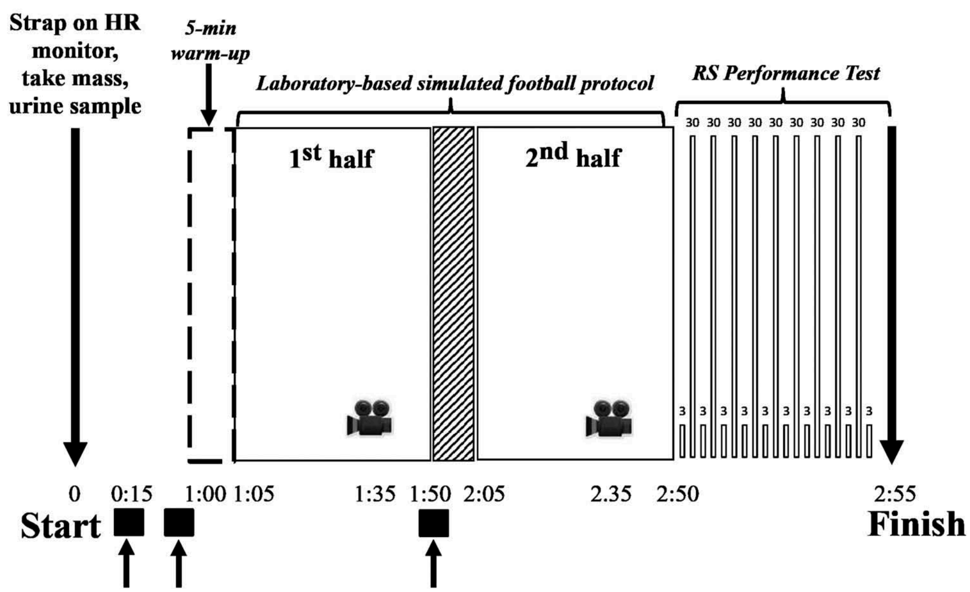

Figure 1. Schematic of the three normobaric hypoxia protocols performed at sea level, 1500 m and 3000-m conditions. % saturation of O2, TC, HR and ratings of perceived exertion (RPE) taken throughout the warm-up, the simulated football-specific protocol, and RS performance test. Rating of effort (0–10 VAS) taken throughout the RS performance protocol; ? indicate fluid ingestion and STROOP test performed at these points. indicates perceptual-cognitive test performed at the 30-min mark during the laboratory-based simulated football protocol.

Procedures

Laboratory-based simulated football protocol

Players arrived 1-h before the start of the test and provided a nude body mass measure and urine sample (Osmocheck pocket pal OSMO, Vitech Scientific Ltd, Japan) and put on a heart rate (HR) monitor (Polar FT1; Polar Electro Oy, Kempele, Finland). During the non-fatigued condition players performed a standardised warm-up consisting of 5-min at 10-km·h^{-1} on a motorised treadmill (Pulsar, H/P cosmos, Nussdorf-Traunstein, Germany) followed by a task-specific warm-up consisting of 50, 70 and 80% of maximal effort sprints for 3-s with 30-s recovery (brief enough not to cause significant fatigue) on a non-motorised treadmill (Woodway, Force 3.0; Waukesha, WI, USA). Following this they performed the RS test. During the three other conditions all players were required to sit down for 45-min and ingest a 600 mL drink consisting of 0.66 g sodium (Table Salt; ASDA, Leeds, UK), 140 mL of sugar-free cordial (Vimto-Nichols plc, Newton Le Willows, UK) and 460 mL water. After the rest period, players ingested the same drink and performed a 5-min standardised warm-up. Players then underwent a validated laboratory-based simulated football protocol on a motorised treadmill designed to replicate a full 90-min game including a 15-min half time recovery period (Drust et al. 2000). During half-time participants ingested the final 600 mL drink. After this all players underwent the RS test. Upon completion, another nude body mass and a urine sample was provided.

Measures of HR, thermal comfort, ratings of perceived exertion and pulse oximetry (% saturation of O_2; Biosync Pulse Oximeter; Contec Medical Systems ltd., Qínhuángdǎo, China) were taken during the warm-up and at every 5-min time-point throughout the football protocol. HR, thermal comfort, ratings of perceived exertion (6 to 20 scale) and ratings of effort (0 to 10 scale; '0' no effort and '10', maximal) were also measured after each sprint. The Stroop test was performed upon arrival, pre-warm-up and at half-time. Further, a video-based perceptual-cognitive skills test adapted for football was presented at the 30-min mark during each half when running activity patterns were of lower intensity (during stationary or walking mode). These time-points were chosen to test whether the latter stages of a game, at elite and sub-elite levels led to more mistakes being made in the last 15-min of a match in the second compared to the first half, and whether differences are present between different levels of hypoxia.

Perceptual-cognitive test

Players were presented with video sequences of dynamic, 11 *vs*. 11 football situations from the first-person perspective of a player during a defensive phase. The video sequences were filmed on a recommended Adult football pitch using a wide-angle converter lens (Canon WD-H72 0.8x, Tokyo, Japan) from an elevated view of approximately 2.75 m, around the penalty spot in the defending's team penalty area. This filming view permitted the field's entire playing width to be observed and provided a better perception of depth during match-play. The details on the production of the video sequences have been reported elsewhere (Roca et al. 2011) but, in brief, are as follows: the film contained 11 *vs*. 9 (the goalkeeper and defensive's team sweeper did not take part) football match play on a full-sized pitch with skilled adult players, which were digitally edited using Adobe Premiere Pro CS4 software (Adobe Systems Incorporated, San Jose, CA, USA) to be utilised for the simulation task. A panel of three UEFA (Union of European Football Associations) qualified football coaches selected the offensive video simulation clips to ensure all clips were representative a football game scenario. Only the approved football simulation clips were used in the test film. The test film included 20 action sequences, approximately

5-s in duration, occluded 120-ms prior to the player in possession of the ball making an attacking pass, shooting at goal, or maintaining possession of the ball by dribbling. Upon occlusion of each video clip, participants were required to report '"What the player in possession was going to do?" (anticipation)' and '"What decision the participant themselves made or were about to make at the moment of video occlusion?"' (decision making).

At the beginning of each action sequence a red dot appeared on a dark background to display where the football would be located in the clip. This allowed players to identify their position on the football pitch and where their teammates and players of the opposing team were located. The photograph of the clip was visible to the player for approximately 1.5-s prior to the phase of play commencing.

Anticipation accuracy was defined as whether or not the participant correctly selected the next action of the player in possession of the ball at the moment of video occlusion (e.g., continued dribbling the ball, passed to a teammate and which teammate, or shot at goal). For the decision-making variable, a panel of three UEFA qualified soccer coaches independently selected the most appropriate decision for a participant to execute in response to the situation at the time of video occlusion on each trial. The accuracy was then defined as whether or not the participant decided on the action selected by the coaches as most appropriate for that trial. Anticipation and decision-making accuracy scores were calculated individually as the mean number of trials (in %) in which the player made the correct response. Players completed 10 test trials per time point, during a time, which the exercise protocol was in stationary or walking mode. The order of the clips was counterbalanced between conditions.

RS test

All testing procedures were performed on a non-motorised treadmill as previously described (see Pullinger et al. 2013), where the position of the player on the treadmill was standardised in accordance with the guidelines set by the manufacturers (Woodway; Waukesha, WI, USA). During the test, treadmill speed, power output and distance covered were sampled at a rate of 200 Hz, leading to 600 samples per variable over the 3-s sprint. Sprint data for peak velocity (PV), average velocity (AV) and distance covered (DC) were recorded with a commercially-designed software program (Pacer Treadmill Software; Innervations, Australia). Fatigue in PV was calculated using the % decrement method as advised by Glaister et al. (2008). Strong verbal encouragement was given during all sessions.

Statistical analysis

Using statistical power software (G*Power v3.1.10, Germany), the sample size required for this study was estimated to be nine. This estimation was based on detecting a meaningful difference of 5% in DC, a statistical power of 0.8 and an alpha level of 0.05 (Morris et al. 2009) between fatigued and non-fatigued conditions. A sample size of nine was also estimated to be large enough to detect meaningful differences of 5% in our other RS outcome variables of PV and AV.

All data were analysed using statistical software (SPSS, Chicago, IL, USA). Differences between conditions were evaluated using a general linear model with repeated measures. To correct violations of sphericity, the degrees of freedom were corrected in a normal way, using Huynh-Feldt ($\varepsilon > 0.75$) or Greenhouse-Geisser ($\varepsilon < 0.75$) values for ε, as appropriate. Graphical comparisons between means and Bonferroni pairwise comparisons were made where main effects were present. Effect sizes (ES) were calculated from the ratio of the mean difference to the pooled standard deviation. The magnitude of the ES was classified as trivial (≤ 0.2), small (> 0.2–0.6), moderate (> 0.6–1.2), large (> 1.2–2.0) and very large (> 2.0) based on guidelines from Batterham and Hopkins (2006). The results are presented as the mean ± the standard deviation throughout the text unless otherwise stated. Ninety-five percent confidence intervals are presented where appropriate and were corrected for between subject differences such as in figures this was done using the method suggested by Atkinson (2001). The approach involves the conceptualisation of the trends over time for the `average person' by normalising subject means and expressing all changes relative to the same mean. The alpha level of significance was set at 5%.

Results

Fatigued vs. non-fatigued at sea level

RS performance measures of DC and AV showed differences following a football match simulation (Table 1A). Following a simulated football protocol DC reduced by 4.8% (mean difference = 0.7 ± 0.3 m, F1, 9 = 8.064, P = 0.019, 95% CI: 0.1–1.3 m; ES = 0.68) and AV by 5.5% (mean difference = 1.0 ± 0.3 km.h–1, F1, 9 = 13.046, P = 0.006, 95% CI: 0.4–1.5 km.h–1; ES = 0.79). Profiles for all RS performance variables dropped over time with higher values during sprint 1 compared to sprint 10 irrespective of condition (P < 0.05). There was no significant interaction in any of the RS performance variables (P > 0.05).

HR and RPE responses to the RS test were significantly higher in a fatigued state (Table 1A) at the end of a laboratory-based football match simulation (P < 0.05). There was no difference in values observed for perceived TC. Effort levels were rated as maximal, 10 out of 10 throughout all conditions and for all sprints.

Hypoxia

RS performance measures showed a main effect for condition and sprint number for DC (Table 1B) with a decline of 6.5% at 1500 m (mean difference = 1.0 ± 0.2 m, $F_{2,\ 18}$ = 28.707, P = 0.008, 95% CI: 0.3–1.6 m; ES = 0.91) and 12.8% at 3000 m (mean difference = 1.9 ± 0.2 m, $F_{2,\ 18}$ = 28.707, P < 0.0005, 95% CI: 1.3–2.5 m; ES = 1.47) compared to sea level. Performance decrements of 6.8% were also observed at 3000-m (P = 0.031; ES = 0.76) when compared to 1500-m.

A main effect for condition and sprint number was also found for AV and PV (Table 1B). AV was significantly reduced

Table 1. Mean (± SD) values for RS variables, and subjective measures in a fatigued and non-fatigued state **(A)**. Mean (± SD) values for RS variables, and subjective measures at sea level, 1500 and 3000 m altitude **(B)**. Statistical significance ($P < 0.05$) is indicated in bold. The magnitude of the ES was classified as trivial (≤ 0.2), small (> 0.2–0.6), moderate (> 0.6–1.2), large (> 1.2–2.0) and very large (> 2.0).

A

Variable	Fatigued	Non-Fatigued	Significance of main effects for condition	Significance of main effects for time	Interaction	Effect Size
Repeated Sprint (RS)						
Distance Covered (m)	14.7 ± 1.1	15.4 ± 1.0	**$P = 0.019$**	**$P = 0.019$**	$P = 0.913$	0.68
Peak Velocity (km h^{-1})	20.5 ± 1.0	20.7 ± 0.7	$P = 0.641$	**$P = 0.001$**	$P = 0.579$	0.19
Average Velocity (km h^{-1})	17.4 ± 1.3	18.4 ± 1.1	**$P = 0.006$**	**$P = 0.017$**	$P = 0.923$	0.79
% decrement in Peak Velocity	3.4 ± 1.7	4.4 ± 3.5	$P = 0.431$	n/a	n/a	0.39
Subjective Measures						
Effort (0–10 cm VAS)	10.0 ± 0.0	10.0 ± 0.0	n/a	n/a	n/a	n/a
RPE (6–20)	15.5 ± 2.4	14.6 ± 1.8	**$P = 0.022$**	**$P < 0.0005$**	**$P = 0.030$**	0.97
Thermal comfort (1–9)	7.6 ± 1.0	7.4 ± 1.1	$P = 0.334$	**$P < 0.0005$**	**$P = 0.038$**	0.23
Heart rate (bpm)	171 ± 8	167 ± 9	**$P = 0.007$**	**$P < 0.0005$**	P = 0.199	0.65

B

Variable	0-m	1500-m	3000-m	Significance of main effects for condition	Significance of main effects for time	Interaction	Effect Size (0–1500 m)	Effect Size (0–3000 m)
Repeated Sprint (RS)								
Distance Covered (m)	14.7 ± 1.1	13.8 ± 1.0	12.8 ± 1.5	**$P < 0.0005$**	**$P < 0.0005$**	$P = 0.681$	0.91	1.47
Peak Velocity (km h^{-1})	20.5 ± 1.0	19.9 ± 1.1	19.2 ± 1.0	**$P < 0.0005$**	**$P < 0.0005$**	$P = 0.825$	0.59	1.29
Average Velocity (km h^{-1})	17.4 ± 1.3	16.3 ± 1.1	15.2 ± 1.8	**$P < 0.0005$**	**$P < 0.0005$**	$P = 0.584$	0.90	1.47
% decrement in PV	3.4 ± 1.7	4.0 ± 2.7	5.4 ± 2.8	$P = 0.179$	n/a	n/a	0.45	0.94
Subjective Measures								
Effort (0–10 cm VAS)	10.0 ± 0.0	10.0 ± 0.0	10.0 ± 0.0	n/a	n/a	n/a	n/a	n/a
RPE (6–20)	15.5 ± 2.4	17.5 ± 2.3	18.0 ± 1.9	**$P = 0.011$**	**$P < 0.0005$**	$P = 0.459$	0.23	0.59
Thermal comfort (1–9)	7.6 ± 1.0	7.7 ± 1.0	7.9 ± 1.0	$P = 0.168$	**$P < 0.0005$**	$P = 0.740$	0.10	0.42
Heart rate (bpm)	171 ± 8	167 ± 12	169 ± 11	$P = 0.439$	**$P < 0.0005$**	$P = 0.533$	0.45	0.29
% O_2 saturation	96.6 ± 2.1	93.0 ± 3.1	83.3 ± 4.6	**$P < 0.0005$**	$P = 0.115$	$P = 0.120$	2.87	6.13

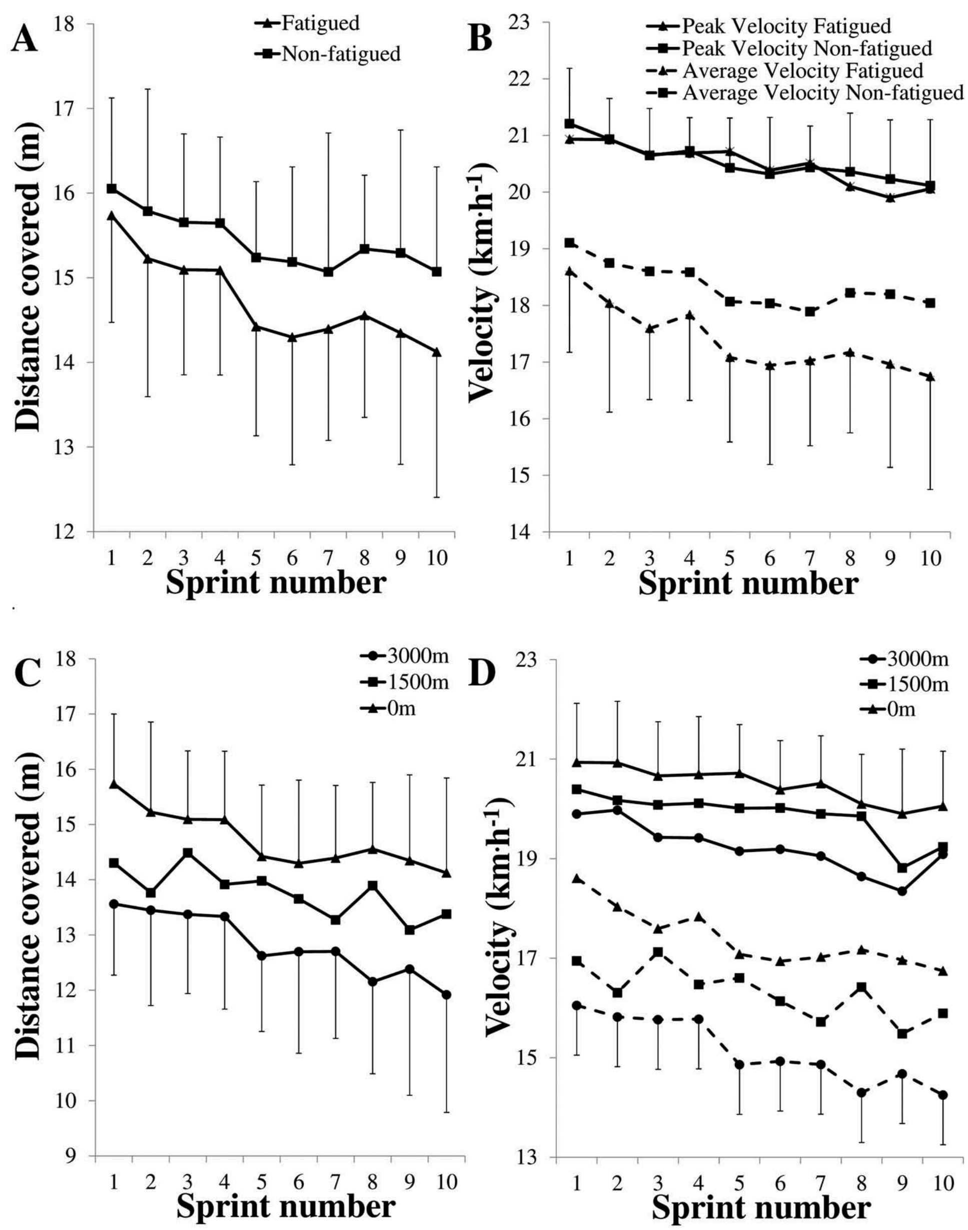

Figure 2. Mean and 95% confidence intervals (corrected for between-subject variability) for distance covered (a), and velocity (peak and average); (b) from sprint 1 to 10 for fatigued (?) and non-fatigued (?) sea level conditions. Mean and 95% confidence intervals (corrected for between-subject variability) for distance covered (c) and velocity (peak and average); (d) from sprint 1 to 10 for RS performance following the football-specific intermittent treadmill fatiguing protocol for sea level (?), 1500 (?) and 3000 m (?). Dashed lines indicate averages and full lines indicate peak values for variables.

by 6.3% at 1500-m (mean difference = 1.1 ± 0.3 km h^{-1}, $F_{2, 18}$ = 27.266, P = 0.009, 95% CI: 0.3–1.9 km h^{-1}; ES = 0.90) and 12.8% at 3000-m (mean difference = 2.2 ± 0.3 km h^{-1}, $F_{2, 18}$ = 27.266, P < 0.0005, 95% CI: 1.4–3.0 km h^{-1}; ES = 1.47) compared to sea level. Performance decrements of 7.0% in AV were also observed at 3000-m ($F_{2, 18}$ = 27.266, P = 0.033; ES = 0.79) when compared to 1500-m. Values of PV were 6.2% lower at 3000-m ($F_{2, 18}$ = 18.805, P < 0.0005; ES = 1.29) compared to sea level and 3.1% lower ($F_{2, 18}$ = 18.805, P = 0.023; ES = 0.62) compared to 1500-m.

There was no main effect for condition in % PV (P > 0.05; Figure 2). Profiles for all RS performance variables dropped from sprint 1 to sprint 10 irrespective of condition (P < 0.05). There was no significant interaction in any of the RS performance variables (P > 0.05).

Subjective measures

Physiological responses of heart rate, RPE and % O_2 saturation levels during the football simulations showed a main effect for condition (P < 0.05). Responses were different at 1500-m and 3000-m compared to 0 m (P < 0.05) and between 1500 m and 3000 m (P < 0.05, Table 1B). TC values were no different between conditions (P > 0.05). Values for heart rate, RPE and TC increased as time went on (P < 0.05), while % O_2 saturation levels were no different over the duration of the protocol (P > 0.05).

During RS performance there was a main effect for condition ($F_{1.240,\ 11.157}$ = 8.503, P = 0.011) and sprint number ($F_{1.436,\ 12.921}$ = 34.456, P < 0.0005) for RPE. Perceived Exertion was 5.3% lower at sea level (17 ± 2, P = 0.039, 95% CI: 0–2) compared with 3000 m (18 ± 2). There was a main effect for time for heart rate ($F_{9,\ 81}$ = 59.282, P < 0.0005). Mean values for heart rate, RPE and TC

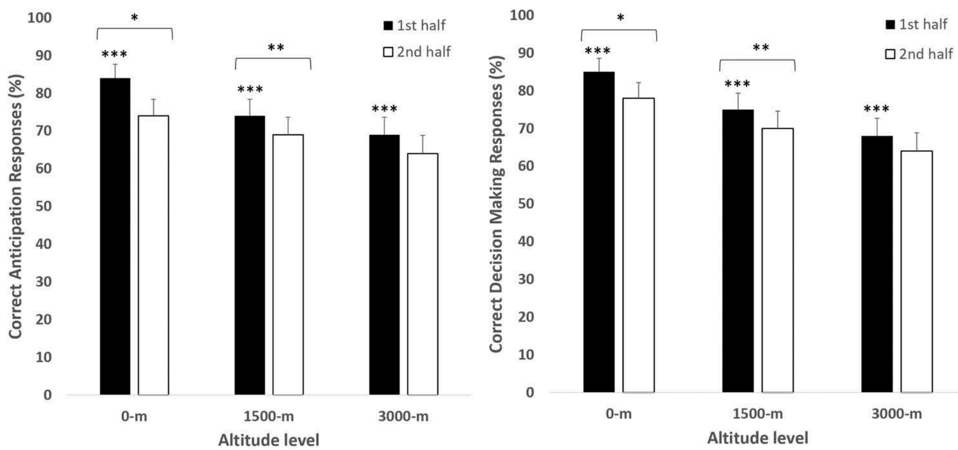

Figure 3. Mean (± SD) values for perceptual cognitive skills test variables at 0 m, 1500 and 3000-m above sea level between the 1st half and 2nd half. *Perceptual-cognitive skill responses significantly higher (P < 0.05) at 0 m compared to 1500 m and 3000 m. **Perceptual-cognitive skill responses significantly higher (P < 0.05) at 1500 m than at 3000 m. ***Perceptual-cognitive skill responses significantly higher (P < 0.05) in the 1st half compared to the 2nd half at all levels of altitude.

increased across all sprints (*P* < 0.0005; Figure 2). Effort levels were rated as maximal, 10 out of 10 throughout all conditions and for all sprints.

Perceptual-cognitive skill responses

There was a main effect for condition ($F_{2,\ 18}$ = 18.025, P < 0.0005) and 1st and 2nd half ($F_{1,\ 9}$ = 7.579, P = 0.022) for decision-making responses (Figure 3). Decision making responses were 15% higher at sea level (82 ± 12%, P = 0.002, 95% CI: 7–24%; ES = 2.22) and 9% higher at 1500 m (73 ± 5%, P = 0.040, 95% CI: 0–13%; ES = 1.39) compared with 3000 m (66 ± 5%). Decision making responses were also more accurate at sea level (82 ± 12%, P = 0.020, 95% CI: 2–17%; ES = 1.17) when compared to 1500 m. Decision making responses in the 1st half were more accurate and decreased in the 2nd half (P = 0.022, CI: 1–10%; ES = 0.90).

There was a main effect for condition ($F_{2,\ 18}$ = 16.765, P < 0.0005) and 1st and 2nd half ($F_{1,\ 9}$ = 45.000, P < 0.0005) for anticipation responses (Figure 3). Anticipation responses were 13% higher at sea level (79 ± 9%, P = 0.002, 95% CI: 5–20%; ES = 2.41) and 5% higher at 1500 m (72 ± 7%, P = 0.025, 95% CI: 0–9%; ES = 1.33) compared with 3000 m (67 ± 5%). Anticipation responses were also more accurate at sea level (79 ± 9%, P = 0.045, 95% CI: 0–15%; ES = 1.35) when compared to 1500 m. Anticipation responses were more accurate in the 1st half and decreased in the 2nd half (P < 0.0005, CI: 4–9%; ES = 1.90). There was no main effect for condition, time or interaction effect the percentage number of mistakes for the 'word' and the 'colour' part of the Stroop test (P > 0.05).

Body mass changes, urine osmolality and sweat rate

Body mass, urine osmolality and sweat rate were not different between hypoxic conditions (*P* > 0.05) There was a 'time' effect with a reduction in body mass (–0.4 ± 0.1 kg; $F_{1,\ 9}$ = 23.984, *P* < 0.005, CI: 0.2–0.6 kg; ES = 0.04) and urine osmolality (–474 ± 38 mOsm kgH_2O^{-1}; $F_{1,\ 9}$ = 23.984, *P* < 0.005, CI: 388–559 mOsm kgH_2O^{-1}; ES = 3.82) post exercise.

Discussion

The first aim of the present study was to investigate whether the RS test (10 × 3-s with 30-s rests) used in this study was sensitive enough to detect differences while players were fatigued. This protocol has only previously been used for time-of-day research (Pullinger et al. 2013). It is therefore important to establish whether the test is sensitive enough to detect a worthwhile change when fatigued (a major factor known to affect performance in football). Previous studies have established a decline in PV and peak power due to several mechanisms related to fatigue during RS performance. Further, previous findings have established RS variables to be highly dependent on the mode of exercise utilised (see Girard et al. 2011). In addition, it has been reported that prior activity highly influences the ability to perform RS due to impaired rates of muscle power output ability (Mendez-Villanueva et al. 2008). We established that DC and AV reduced by 5–6% when individuals were fatigued and found that heart rate and RPE responses were higher. Although, no differences were found for PV and % decrements for velocity in individuals between both conditions. These are difficult aspects of RS performance to measure on a non-motorised treadmill, as they only present a fraction of work done in a 3-s period (Pullinger et al. 2013). It has been established that the ability to maintain sprint performance during RS has been linked to rates of $\dot{V}O_2$ recovery and varies between individuals (Dupont et al. 2010).

Certifying that our RS test was able to detect meaningful changes in a fatigued state, our study aimed to establish the magnitudes of changes in RS performance and perceptual-cognitive skill responses during a laboratory-based simulated football at varying degrees of hypoxia. While the effects of acute hypoxia on football performance and RS performance have been studied extensively, there is little research into the effects of perceptual-cognitive skills, such as anticipation and decision making. Previous research has concluded that hypoxia has negative effects on cognition (McMorris et al. 2017). Whether the ability to anticipate and make decisions which are crucial to skilled performance in football (Williams et al. 2012; Roca et al. 2013) displays similar findings is currently unknown. The present study found that the laboratory-based match simulation negatively impacted anticipation accuracy and decision-making ability in hypoxia and between halves. It has previously been established that prolonged intermittent exercise influences the perceptual-cognitive processes in football (Casanova et al. 2013). In agreement, the present study established that perceptual-cognitive skills decreased by 5% between halves (irrespective of hypoxia), with deterioration being attributed to fatigue. However, traditionally, studies that have examined the effects of exercise on perceptual-cognitive performance, have tended to vary greatly. The choices of perceptual-cognitive tasks utilised in previous studies do not assess aspects related to perception and/or cognition related to football. Very few use tasks which examine each perceptual-cognitive skill in isolation from one another. In doing so, the present study established that players were less accurate at anticipating the action of opponents (8%) and deciding the appropriate course of action (9%) at 1500 m compared to sea level. As altitude levels reached 3000-m anticipating the action of opponents and deciding the appropriate course of action further decreased (by 13% and 15% respectively).

We know football requires players to anticipate actions of teammates and opponents and are required to make decision sunder varying exercise intensities and that these are critical to high-level football performance. Previous research has found players to be negatively affected when they are both physically and mentally fatigued (Smith et al. 2016). In agreement, we established that the negative impacts of fatigue on performance resulted in our players' inability to accurately anticipate football specific video sequences or make the correct decision. Further, we also established that perceptual-cognitive ability in football was impaired, in agreement with previous suggestions (Ando et al. 2013). A combination of fatigue and hypoxia compromises perceptual-cognitive ability through a combination of underlying mechanisms (Ando et al. 2013; Casanova et al. 2013). Therefore, it can be established that perceptual-cognitive responses in football, potentially illustrates a dose response in relation altitude and time, such that with increasing altitude and fatigue negatively effects these tasks. Negative changes in the ability to make decisions and anticipate actions because of fatigue and acute hypoxia could help provide an explanation as to why more mistakes are made and more goals are scored during the latter stages of each half in a game.

Impairments of 6.5% in DC, 6.3% in AV and 3.1% in PV following prior activity (a laboratory-based simulated football) were apparent when exposed to acute hypoxia of 1500-m. Even larger decrements were established at 3000-m (6.2–12.8%). In agreement with previous data which found total DC decreased by 3% at levels of 1200-m (Nassis 2015), with further reductions present at higher levels of hypoxia (Garvican et al. 2014). This data acquired through football match-play requires caution in interpretation as match-specific factors (such as opposition, current score line and tactics) and acute hypoxia exposure (reduction in partial pressure of O2) result in pacing strategies and exercise intensities to be altered to avoid early fatigue (Brocherie et al. 2017). Therefore, the use of a laboratory-based match simulation in a highly controlled environment enabled us to establish more definitive inferences regarding the true isolated impact of acute hypoxia on various performance metrics (Drust et al. 2007; Taylor and Rollo 2014). The present study used a motorised laboratory-based football-specific protocol to simulate the physiological demands of a match (Drust et al. 2007) to assess the magnitude of change in RS performance at the end of a match simulation for a standardised work rate.

Previous research has examined the effects of different levels of hypoxia on RS performance across many experimental designs with and without prior exercise taking place post RS test. Impairments in RS performance have been found in varying hypoxic environments when directly compared to sea level (Bowtell et al. 2014; Brocherie et al. 2016, 2017; Girard et al. 2016). Hypoxia has been found to negatively affect running mechanical performance (Brocherie et al. 2016) and physiological responses (Bowtell et. 2014), thus further accentuating the inability to perform RS. Differences between exercise protocols and mode of exercise call into question the sport-specific relevance and validity of many RS tests utilised in the literature (Spencer et al. 2005). Further, time-motion analysis findings in football suggest that the mean duration of sprints is no longer than 3-s equating to approximately ~15-m in distance (Marshall et al. 2016). Considering previous research has only examined the impact of varying altitudes on RS performance but not looked at incorporating perceptual cognitive skills, it makes comparisons between the current research and other research studies difficult. The severity of hypoxia and changes in match-specific factors which determine to which extent fatigue increases during an actual game and how RS performance differs during the latter stages is currently unknown. Therefore, it would be prudent to investigate what affect a laboratory-based match simulation has at varying degrees of hypoxia on RS performance and perceptual-cognitive skills.

In contrast to previous research (Bowtell et al. 2014; Brocherie et al. 2016, 2017), all RS performance variables during the RS test were impaired during the first sprint at 1500-m and further decreased at 3000-m. Players were unable to alter exercise intensity and pacing strategies as all conditions had a given physical load. This meant players were unable to modulate physical performance to avoid premature and/or more pronounced fatigue. It has been found that considerable decrease in muscle glycogen present at the end of a game, the thermoregulatory strain, a reduced central drive from the nervous system and central fatigue all play a major role in the inability to perform RS (Reilly et al. 2008). At hypoxia, further alterations in cardiorespiratory, circulatory and muscular fitness components results in a clear dose-response relationship regarding altitude. The present results showed alterations in HR between conditions with marked increases present at higher levels of hypoxia. This means, an increase in additional stress upon the human body and the inability to sustain given work-rates in RS performance due to muscle fatigue, result in a linear decrease in RS performance variables with increased levels of hypoxia. Accordingly, increased levels of acute hypoxia exposure resulted in RPE responses to increase in correlation with higher levels of hypoxia due to the relative perceived intensity or difficulty of any given absolute level of exercise to be higher (Levine et al. 2008).

The present study has important limitations that should be pointed out. Although we presented players with a video-based perceptual-cognitive skills test adapted for football at the 30-min mark during each half (when most goals are scored/conceded), we did not measure perceptual-cognitive skills at any other time-point. Hence, we are unable to confirm the exact changes which occur during a game. Whether changes because of hypoxia and fatigue on perceptual-cognitive skills are different compared to other time-points is beyond the scope of this study. Finally, whether the same findings would occur in professional players is unknown and would require more in-depth research.

Practical implications

Our study provides novel information and shows that following a laboratory-based simulation of a football match, RS performance and perceptual-cognitive skills are impaired at altitude for a given physical workload. In agreement with previous research, we further establish that hypoxia and fatigue lead to an impairment in RS performance and perceptual-cognitive skills related to football. If appropriate acclimatisation or exposure prior to competition has not been undertaken, a profound adverse effect on football performance (both physiologically and psychologically) will be apparent and significantly worsens as altitude increases when fatigued. However, the underlying mechanisms which are responsible for the impairment of performance still need to be thoroughly documented and will help provide pertinent information for coaches and athletes competing at altitude. To ensure marked decreases in physiological and cognitive capabilities are avoided, coaches and sports science staff should plan several days of specific acclimatisation or acclimation prior to playing official football matches at altitude. In doing so, players and the outcome of the match will be less affected. Therefore, a short acclimatisation period of 3–5 days prior to playing at 1500 m may be useful to approach peak football performance, with longer periods of acclimatisation when playing at more extreme levels of altitude. It is worth noting that altitude has a profound effect on human physiology and during acclimatisation sessions it is vital to measure how the body is reacting. In practical terms, this may be done using a portable pulse oximeter to assess % saturation of O_2 continuously or 10-min intervals, knowing that values at commonly observed at sea level are 99–100%. Further, exposure to altitude displays large inter-individual differences in how people respond and react to altitude exposure. Therefore, should a player be a 'bad' responder to altitude, it is worth knowing as this informs the coach and medical staff as to whether the player should go to altitude and play if the appropriate acclimatisation period cannot be undertaking. Considering a long adaptation period is not always possible, and hypoxia negatively affects physiological and cognitive capabilities, further scientific observations are required to reach a new and updated consensus.

Conclusion

The data demonstrate that the RS test was highly sensitive to fatigue and hypoxia for a given physical load. Further, perceptual-cognitive skills and RS performance measures decreased during a laboratory-based match simulation. Additional research further investigating the underlying mechanisms responsible for the impairment of RS performance and single sprint performance at the end of a football game, be it naturally or metabolically mediated, would certainly add to the existing research on this topic. Investigating acclimatisation protocols would provide further understanding regarding altitude-induced impairment in RS performance and perceptual-cognitive skills, but this was not our aim.

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