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Fundamental relationships of executive functions and physiological abilities with game intelligence, game time and injuries in elite soccer players

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Summary

The study examined the (1) interrelation of cognitive-athletic performance concerning game time and (2) injuries; (3) relation between executive functions and game intelligence. A total of 172 elite soccer players (age: 12–34 years) performed tests assessing multiple-object-tracking, working memory capacity (WMC), cognitive flexibility (CF), and inhibition. General and specific-endurance-performance, and physical performance (jumps and sprint) were also measured. Game intelligence, time and injuries were tracked. WMC, CF, and a total cognition score showed correlations with game intelligence, and the same parameter, along with selective attention and game intelligence were also correlated with game time. Sprint and specific-endurance were connected with game time, whereas contact injuries only correlated with sprint, and noncontact injuries with sprint and general-endurance. Especially executive functions represent fundamental associations with game intelligence and -time across all age groups, whereas certain physiological abilities may contribute to more game time and less non-contact injuries depending on age.

KEYWORDS

cognitive functions, high-performance athletes, physiological performance, talent prediction

1 | INTRODUCTION

The prediction of talent across all ages is a crucial aspect of high-performance settings (Coulson-Thomas, 2012). One of these settings is team sports like elite soccer, where certain physical, physiological and cognitive skills are required to operate on an extraordinary level (Memmert, 2021). Identifying the principal mechanisms of high-performance of all age groups in this sport is of common interest as soccer is a largescale phenomenon with 265 million players around the world (FIFA, 2013). Hence, soccer associations and clubs need to find the players among the large amount with certain characteristics enabling them to succeed later or currently in their career on a professional level. However, the extent to which a combination of physiological and cognitive skills contributes to success in elite soccer is still unclear (Rein & Memmert, 2016; Murr, Feichtinger, et al., 2018; Murr, Raabe, & Höner, 2018; Williams et al., 2020). Thus, the present study is unique as it aims to examine the effect size of the contribution of both abilities to success of youth as well as adult elite soccer players.

Though, previous studies examined how certain objective performance parameters may contribute to success in isolation. The majority of these investigations had a monodisciplinary focus on physical (e.g., height and weight) or physiological (e.g., endurance and speed) determinants whereby the latter has been partially related to success in soccer (for reviews see Murr, Raabe, & Höner, 2018; Williams et al., 2020). However, it is well-known that success in a complex game like soccer depends on multidisciplinary, symbiotic aspects which need to be investigated in study designs which represent that multidisciplinarity according to best practice guidelines (Baker et al., 2020; Johnston et al., 2018; Rees et al., 2016; Till & Baker, 2020; Williams et al., 2020). However, these guidelines have rarely been applied in previous studies (Johnston et al., 2018; Williams et al., 2020) whereas first evidence indicates that physiological and cognitive skills may be crucially interrelated (Scharfen & Memmert, 2019b). The expert performance approach—analyzing sports-specific cognition—has already pointed out the relevance of cognition in team sports (Mann et al., 2007). This approach has recently been complemented by the cognitive component skills approach—analyzing domain-general cognition (Scharfen & Memmert, 2019a; Voss et al., 2010). Current models propose that especially the domain-general cognition is an important part of this multidisciplinarity as well, besides physiological characteristics (Baker et al., 2019; Baker et al., 2020; Johnston et al., 2018; Rees et al., 2016; Till & Baker, 2020; Vaeyens et al., 2009). Thus, recent studies established a promising association to elite performance especially present in soccer (Huijgen et al., 2015; Sakamoto et al., 2018; Scharfen & Memmert, 2019a; Verburgh et al., 2014, 2016; Vestberg et al., 2012, 2017, 2020).

These first studies represent an encouraging value of domain-general cognition for talent identification but evidence on their contribution to success in elite soccer, especially across several age groups is scarce as the majority of the investigations had a monophasic focus (i.e., the examination of only one specific phase of development/age group; Ivarsson et al., 2020; Johnston et al., 2018; Sakamoto et al., 2018; Vestberg et al., 2012, 2017, 2020; Williams et al., 2020). Specifically, a crucial subgroup of these cognitive skills are the executive functions defined as cognitive processes that regulate thought and action, especially in nonroutine situations (Diamond, 2013; Friedman et al., 2006; Miyake & Friedman, 2012). They include (i) working memory: holding information in mind and mentally working with it; (ii) cognitive flexibility (CF): changing perspectives or approaches to a problem, flexibly adjusting to new demands, rules, or priorities and (iii) inhibitory control: control one's attention, behavior, thoughts, and/or emotions to override a strong internal predisposition or external lure, and instead do what's more appropriate or needed (Diamond, 2013). Furthermore, best practice guidelines also propose the inclusion of coach-rated evaluation which has been rarely conducted previously (Williams et al., 2020).

A first attempt to analyze those coach-rated criteria for the cognitive domain showed that the coaches' assessment of game intelligence is moderately correlated with executive functions' objective parameters in adult elite soccer players (Vestberg et al., 2020). Nevertheless, this interrelation has not been shown in adolescents yet, and the extent to which a combination of these coach-rated- and objective cognitive parameters relate to success is still unknown.

Another line of research concerning performance data emphasizes that high injury-risks are associated with poor cognitive functioning (Giesche et al., 2020; Monfort et al., 2019; Swanik et al., 2007). However, the association of behavioral data for real injuries and not only injury-risks needs further evaluation (Ivarsson et al., 2017). More specifically, the differentiation between contact and non-contact injuries is relevant due to the contrasting underlying mechanisms and their distinct incidence numbers (Swanik et al., 2007).

However, by reviewing the literature on previous endeavors to identify key characteristics of talent and injuries, it becomes evident that the common focus was (1) rarely a combination of cognitive and physical characteristics and (2) monophasic by either focusing on adults or adolescents. Although first investigations of the association between cognitive performance and success in elite soccer are promising this area is still in its infancy and also quite debatable (Beavan et al., 2020). Additionally, the coach-rated assessments of this cognitive performance and its interrelation with objective cognitive parameters are mostly unknown and, previous examinations only included adults. Thus, using a multiphasic focus by integrating both age groups may also evaluate for the first time how large the effects of certain relationships are across all tested age groups. Consequently, it could be analyzed to what extent fundamental associations exist for soccer expertise at every developmental phase. This would yield valuable insights in terms of (a) a performance-needs analysis of current demands of high-performance in complex team sports like soccer and (b) a more sophisticated understanding of the contribution of cognitive and physiological skills of expertise and talent to certain developmental stages (Baker et al., 2019, 2020; Johnston et al., 2018; Till & Baker, 2020).

Based on the outlined literature gaps, the aim of the present study on adolescent and adult elite soccer players (i.e., 12–34 years of age) is threefold. First, the multidisciplinary and multiphasic performance data, including physiological and cognitive (objective and coach-rated) parameters, are examined in two regards: (1) as a primary aim in terms of success defined as the playing time per player in games which is a commonly used performance indicator (Rumbold et al., 2020) and (2) as a secondary aim in terms of injury incidence (i.e., contact and non-contact). Further, the extent to which coach-rated game intelligence and objective assessments of executive functions are interrelated is analyzed as an exploratory aim as well as the subgroup comparison of youth and adult players. Moreover, based on previous literature it is hypothesized that (1) a moderate effect of better physiological and cognitive skills on more playing time and (2) fewer injuries exists which is independent of age and (3) game intelligence correlates moderately with executive functions. Taken together, the purpose of the present study is to generate a more holistic understanding of the extent to which executive functions contribute to high-performance sports in terms of success and injury prevention.

More specifically, game intelligence, executive functions and attention (multiple-object tracking) are analyzed based on their crucial role in elite soccer (game intelligence Vestberg et al., 2020; executive functions Huijgen et al., 2015; Scharfen & Memmert, 2019a; Verburgh et al., 2014, 2016; Vestberg et al., 2012, 2017; multiple-object tracking (Faubert, 2013; Romeas et al., 2016). Physiological abilities are included as they are important performance properties of high-level game performance (Abade et al., 2014; Bangsbo et al., 2008; Murr, Raabe, & Höner, 2018; Unnithan et al., 2012; Waldron & Murphy, 2013) and are commonly examined in the talent prediction studies of the physiological domain (Murr, Raabe, & Höner, 2018; Williams et al., 2020). Additionally, we are following several calls (Baker et al., 2020;

Johnston et al., 2018; Rees et al., 2016; Till & Baker, 2020; Vestberg et al., 2020; Williams et al., 2020) to conduct multidisciplinary, multiphasic and longitudinal research including coach-rated assessments and aim to expand previous findings (Vestberg et al., 2020) in a similar study design with a larger population also including adolescents.

2 | METHODS

2.1 | Participants

A total of 172 male elite soccer players (12–34 years of age) from the youth academy's talent development program ($n = 145$) and the first team ($n = 27$) of a professional German soccer club were recruited. However, the dataset was not complete for all of the 172 players as some performance data were missing either i) at random (missing: CMJ, DJ: 4.6%; game intelligence: 14.6%; selective attention, cognition score: 23.7%; acceleration [5 and 30-meter]: 31.3%; RIEA, SJ: 55%; performance-IAT: 65.6%) due to injuries, illness other absence reasons in those tests that were conducted in certain teams (e.g., RIEA in U14-U19) or ii) systematically as some physical tests were not performed in certain teams (e.g., RIEA in U13, U23 and first-team) as analyzed by Little's missing completely at random (MCAR) test (Little, 1988) which were consequently not included in the further analysis. At the time of data collection, their teams played at the top level of their respective age group (U13 with $n = 17$, U14 with $n = 21$, U15 with $n = 20$, U16 with $n = 21$, U17 with $n = 19$, U19 with $n = 22$, first team with $n = 27$) or at the fourth-highest senior league (U23 team with $n = 24$). Participants were not diagnosed with any behavioral, learning, or medical conditions that might influence cognitive abilities. Written informed consent was obtained from every participant or their legal guardian before commencing the tests. The study was carried out by the Helsinki Declaration of 1975 and was approved by the ethics committee of the German sports university cologne. Executive functions are analyzed in terms of working memory, **CF**, inhibition, and attention is investigated by multiple-object tracking. Physiological abilities are examined in terms of endurance performance with an incremental field test (i.e., performance at the individual anaerobic threshold (IAT) and a YoYo intermittent recovery test (i.e., maximal performance stage stating the ability to perform intense exercises repeatedly [RIEA]). As well as in terms of physical performance: with vertical jumps (i.e., squat jump (SJ), counter-movement jump (CMJ), drop jump (DJ)), and with a 30-m sprint.

2.2 | Procedure and materials

Data of cognitive tests were collected in a quiet room. The cognitive tests consisted of one 45-minute session and were conducted before a training session with a sufficient familiarization period (i.e., explanation with test trials) for every measurement. A four-task battery was used to explore the performance of executive functions. Each task started with practice trials in the beginning and is described below. Fixed test order was used, a standard method in neuropsychological assessment: (1) working memory, (2) **CF**, (3) inhibition and (4) multiple-object tracking. All participants were asked to sit in a comfortable position leaning against the backrest of the chair so that the screen distance was the same for all the players. Physiological performance data were collected on a separate session and are described in detail below. All cognitive and physical data were obtained during the first 3 weeks of the season 2020/2021. The reason for the differing sample sizes contributing to the individual correlations is that not every test was conducted in every age group due to the constraints of the club's organization. Leaders of the test batteries were experienced sport scientists and athletic coaches. Nevertheless, this does not change the possible valuable insights generated from this study as the results are interpreted along with their confidence intervals, effect sizes and contributing sample size which allows for comparison of findings even among differing sample sizes (Cumming, 2014).

2.3 | Executive function tests

Working memory capacity (WMC) was measured using the well-established working memory span test by Conway et al. (2005). It measures the player's skill to direct attention toward the present task without getting distracted by other thoughts. More precisely, a counting span task was applied (see Kane et al., 2004 for a detailed description), as this processing task's simplicity allows a widespread application (Conway et al., 2005). The instructions were presented as written text on the computer screen. The counting span task was to count specific shapes among distractors and afterward remembering the count totals for later recall. Every stimulus image included randomly arranged dark blue circles, green circles, and dark blue squares. The task of the participants was counting the dark blue circles and then the total count at the end. A recall mask was presented after 2–7 stimulus images into which participants had to fill their memorized count totals in the exact order they had been illustrated in. The participants counting span score was a partial credit load score (cf. Conway et al., 2005), which represents the sum of all correctly recalled elements—whereby a correctly remembered piece from a set containing two elements receives 2 points, and a correctly remembered element from a set with 7 items receives 7 points—divided by the maximum possible score. Good reliability and validity are stated for the test (ICC = 0.7–0.9; Conway et al., 2005). The test included 15 trials. The dependent measure was the score of correctly memorized objects in percentage representing the WMC (Scharfen & Memmert, 2019b).

CF was measured with the trail making test (TMT) including two parts (A and B) (Sánchez-Cubillo et al., 2009). The TMT-A is commonly used to measure visuo-perceptual abilities whereas TMT-B is used to assess CF (Crowe, 1998). A smaller B-A difference indicates better CF (for a detailed description see Huijgen et al., 2015). A validated tablet version of the TMT was used, which is congruent with the traditional pen-paper version (Delbeare & Lord, 2015). General validity and reliability of the TMT are high (Cronbach's alpha = 0.9; ICC = 0.86–0.94; Smith et al., 2008; Wagner et al., 2011).

Inhibition was assessed with a computer-based language-independent stop-signal task (SST) from the Cambridge Neuropsychological Test of Automated Battery (CANTAB; Cambridge Cognition 2019). The participant's response inhibition was essentially measured by asking them to take part in two opposing tasks: a Go task and a Stop task. They were instructed to press a left-hand button when an arrow occurred which pointed to the left, and a right-hand button when the arrow pointed right (i.e., Go task in 75% of trials). Additionally, they were instructed to inhibit the response and not press any buttons when they heard an auditory "beep" signal (i.e., Stop task in 25% of trials). The onset of the "beep" signal varied in dependence on a staircase protocol (i.e., either decreased or increased) which was based on their performance in the previous trial. The dependent variable is the stop-signal reaction time (SSRT) which is an estimate of the time a participant needed to stop his or her response minus the mean delay, with shorter SSRTs indicating better inhibitory control (Matzke et al., 2018). More detailed information about the test protocol has been described previously (Matzke et al., 2018). SSRT is highly reliable (split-half reliability = 0.91; Williams et al., 1999).

Multiple-Object Tracking was analyzed with the NeuroTracker 3D-MOT task with the NeuroTracker™ Core Program by CogniSens Athletics Inc. from the University of Montreal. The program was displayed on a wall via a video projector. The task included eight balls of which four are marked for 2 s. Then, the four marked balls needed to be tracked for 8 s. Afterward, the tracked balls are required to be stated to analyze the performance. Other settings were the same as in Faubert (2013).

The value cognition-total was calculated by adding the z-standardized scores of all cognitive tests and dividing the sum by the number of included tests.

2.4 | Assessment of game intelligence

The head coaches of each team (i.e., eight in total) were asked to judge their players' game intelligence compared to what they perceive as the average level of their respective league and age group (e.g., German Bundesliga for the first team) as a questionnaire on a one-item assessment. Similar to a previous study, a stanine-scale was used with 5 representing the average of their league and age group, 1 is the lowest and 9 the highest value (Vestberg et al., 2020). Again, similar to Vestberg et al. (2020) no predefined definition of game intelligence was stated as there is no exact definition (Stratton et al., 2004; Wein, 2004) but professional coaches of elite teams have a homogenous and robust opinion of its compounds and level in players. Accordingly, we inferred that their evaluations may be an appropriate measure of player's game intelligence level. Further, to ensure the objectivity of this game intelligence evaluation the ratings of the sports director of the respective age groups were analyzed as well and in addition to the ratings of the coaches of the team. A high degree of inter-rater reliability among the ratings of the sports directors and the respective coach was present as the average measure ICC was 0.82.

2.5 | Physiological tests

A sufficient familiarization period (i.e., explanation with test trials) was conducted before every measurement.

The IAT represents the maximal exercise intensity that can be sustained for a continued period without lactate substantially building up in the athlete's blood. IAT was assessed with a staircase-field test following the protocol of Faude et al. (2014) with the difference that the protocol was the same for every player - initial speed was 9 km/h and speed of the last stage was 16.5 km/h. Running speed was increased every 3 min by 2 km/h and the test was terminated when participants were not able to follow the given speed anymore. To determine the IAT, capillary blood samples (20 μl) were taken from an earlobe at rest and during 30-second breaks between stages and at 1, 3, 5, 7 (Faude et al., 2014). High reliability and validity are stated for this test (González-Haro et al., 2007).

Vertical jump performance was assessed by (1) countermovement jump (CMJ), (2) squat jump (SJ), (3) drop jump (DJ) (box height = 35 cm) on a contact mat (Smart Jump; Smart speed, Fusion Sport, Australia). The protocol of Faude et al. (2014) was applied except for jumping with arm usage to represent soccer-specific demands. Excellent reliability and validity are stated for this test (ICC = 0.99; Rodriguez-Rosell et al., 2016). Dependent measures for CMJ and SJ were height and a quotient for DJ (i.e., DJQ), the calculated relation of height and contact time which were measured using a contact mat with the electrical signal transmitted to a personal computer (Smart speed, Fusion Sport, Australia).

Sprint performance was assessed with infrared timing gates (Smart speed, Fusion Sport, Australia). The protocol of Faude et al. (2014) was applied with a starting line 0.5 m behind the first timing gate whereby resting time was 3 min and only the best 5- and 30-m time was included as the dependent variable. For each player, testing conditions were constant intraindividual.

The repeated intense exercise ability (RIEA) was assessed with the YoYo intermittent recovery test level 1 by following the protocol of Krustrup et al. (2003) and consisted of 2 x 20-m runs back and forth between the starting, turning, and the finishing line at a progressively increased speed administered by audio beeps from a tape recorder. All tests were applied on a soccer pitch with artificial grass, and players conducted a standardized warm-up before starting the test. Excellent reliability (ICC = 0.98) and validity are stated for this test (Deprez et al., 2014; Krustrup et al., 2003). The dependent variable is the maximal reached performance stage.

2.6 | Game time

Game time was evaluated during the beginning of the season 2020/2021 till the end of October, resulting in a minimum of three and a maximum of eight games per team. The reason for this cut-off was the ceasing of the regular soccer leagues. Game time for each player was noted by using the club-internal data records. To gain a standardized game time score for each player independent of age group and their overall differing game durations (i.e., minutes), the percentage of the maximal possible game time was calculated. For example, if a player was not injured or ill but able to play and played one half time in each of the eight games the percentage is calculated as follows: maximal possible game-time percentage = 100%, actually played game-time = 50%. This maximal possible game-time percentage was reduced to 0% when the absence reason of a player was an injury or illness, whereas the score remained at 100% if the lack was due to performance reasons.

2.7 | Injury incidences

Injuries of the same period as game time were diagnosed by the club's medical staff and recorded if that injury prevented a player from taking a full part in all training and match-play activities typically planned for that day and prevented participation for a period greater than 24 h. This reflects the definition of Brooks et al. (2005) and conforms to the consensus definition for team sport athletes (Fuller et al., 2007). The diagnosed injuries were further classified in terms of mechanism (i.e., contact or non-contact), injury type and location which is also based on the consensus definition for team sport athletes (Fuller et al., 2007).

2.8 | Statistical analysis

Data were analyzed using IBM SPSS Statistics 26.0.0. Current recommendations to focus on estimation for best reporting and analysis practice were followed instead of conducting null-hypothesis significance tests (Cumming, 2014); effect-sizes with 95% confidence intervals are reported. Not all variables were normally distributed, as assessed by Shapiro–Wilk's test ($p < 0.05$). Therefore, Spearman's correlation coefficient test was used to investigate the correlation between the player's cognitive, physiological performance and game intelligence, game time and injuries. Correlation coefficients (Spearman's r) of 0.1, 0.3, and 0.5 represent small, moderate, and large effect size estimates, respectively (Cohen, 1988). To confirm that other factors did not confound the findings, we also performed a non-parametric partial correlation analysis (Conover, 1999), which controlled the age group.

3 | RESULTS

Partial Correlations (Spearman's r) with their 95% confidence intervals and the sample sizes contributing to each correlation are stated in Tables 1, 2 and 3. Bivariate correlations and the exploratory youth-adult subgroup analysis are presented in the Appendix. A preliminary analysis (i.e., ANOVA) showed that the slightly different performance level of the U23 compared to the other teams did not influence the results substantially. Generally, results with confidence intervals not including zero are meaningful as they depict reasonable evidence of a population effect (Cumming, 2014).

3.1 | Game intelligence

WMC, CF and the cognition score showed small to moderate correlations with game intelligence. In contrast, selective attention only showed a trend toward a meaningful correlation and inhibition showed no correlation at all. The partial correlation analysis revealed no association of age group on executive functions and game intelligence (see Table 1).

3.2 | Game time

Moderate to large correlations with game time were present for game intelligence and CF whereby WMC, cognition score and selective attention correlated small to moderately with game time. None of the other parameters showed meaningful correlations. After controlling for the age group, the correlations with game intelligence, CF, WMC, cognition score and selective attention remained. In contrast the correlations with RIEA and acceleration (5 and 30 m) became meaningful on a moderate to large level as well (see Table 2). Further, the exploratory youth-adult subgroup analysis showed small to large effect sizes for correlations with all cognitive parameters except for inhibition, and small to moderate effect sizes for correlations with both acceleration times in the youth group. Contrary, the adult group only showed small to moderate correlations with working memory and CF and also a moderate to large effect for inhibition.

3.3 | Injuries

3.4 | Contact injuries

Only 30-m acceleration showed a small to moderate correlation with contact injuries ($n = 13$) whereas CF only showed a trend. None of the other parameters were meaningfully correlated. The correlation

TABLE 1 Partial correlations between executive functions and game intelligence while controlling for age group

	Selective attention	Working memory	Cognitive flexibility	Inhibition	Cognition score
Game intelligence Spearman's r	0.16	**0.28**	**0.30**	0.07	**0.29**
CI	−0.02, 0.33	**0.13, 0.42**	**0.15, 0.44**	−0.09, 0.22	**0.12, 0.45**
n	116	**156**	**156**	156	**116**
Included teams	U15- first-team	U13- first-team	U13- first-team	U13- first-team	U15- first-team

Note: Boldface numbers highlighting CIs not including zero.

TABLE 2 Partial correlations between executive functions, physiological abilities and game time while controlling for age group

	Game intelligence	Selective attention	Working memory	Cognitive flexibility	Inhibition	Cognition score	RIEA	Sprint (5 m)	Sprint (30 m)	Squat jump	Counter movement jump	Drop jump	Performance-IAT
Game time Spearman's *r*	**0.42**	**0.22**	**0.29**	**0.34**	−0.17	**0.29**	**0.32**	−**0.34**	−**0.37**	−0.01	0.04	0.14	0.16
CI	**0.25, 0.56**	**0.02, 0.40**	**0.12, 0.44**	**0.18, 0.48**	−0.33, 0.01	**0.10, 0.46**	**0.10, 0.54**	−**0.50,** −**0.16**	−**0.53,** −**0.19**	−0.27, 0.25	−0.14, 0.22	−0.04, 0.31	−0.15, 0.44
n	**109**	**97**	**128**	**128**	131	**100**	**56**	**103**	**103**	56	122	122	42
Included teams	U13-first-team	U15-first-team	U13-first-team	U13-first-team	U13-first-team	U15-first-team	U14-U19	U13-U23	U13-U23	U15-U19	U13-first-team	U13-first-team	U16-U19

Note: RIEA: repeatedly intense exercise ability; IAT: individual anaerobic threshold; boldface numbers highlighting CIs not including zero.

TABLE 3 Partial correlations between executive functions, physiological abilities and injuries while controlling for age group

	Game intelligence	Selective attention	Working memory	Cognitive flexibility	Inhibition	Cognition score	RIEA	Sprint (5 m)	Sprint (30 m)	Squat jump	Counter movement jump	Drop jump	Performance-IAT
Contact Injury Spearman's *r*	−0.14	0.04	−0.02	0.12	−0.08	−0.04	0.08	−0.08	−**0.24**	0.09	0.12	0.04	−0.04
CI	−0.31, 0.04	−0.15, 0.23	−0.18, 0.15	−0.05, 0.30	−0.24, 0.09	−0.23, 0.15	−0.18, 0.33	−0.26, 0.10	−**0.41,** −**0.06**	−0.16, 0.33	−0.05, 0.28	−0.13, 0.21	−0.32, 0.25
n	122	108	141	141	141	108	61	115	**115**	66	134	134	48
Noncontact Injury Spearman's *r*	0.08	−0.14	0.11	0.05	0.16	0.14	−0.20	0.11	**0.35**	−0.12	−0.19	0.16	−**0.29**
CI	−0.10, 0.25	−0.32, 0.10	−0.10, 0.27	−0.12, 0.21	−0.01, 0.32	−0.05, 0.32	−0.43, 0.05	−0.07, 0.30	**0.18, 0.50**	−0.35, 0.13	−0.35, 0.02	−0.01, 0.32	−**0.53,** −**0.01**
n	122	108	141	141	141	108	61	115	**115**	66	134	134	**48**
Included teams	U13-first-team	U15-first-team	U13-first-team	U13-first-team	U13-first-team	U15-first-team	U14-U19	U13-U23	U13-U23	U15-U19	U13-first-team	U13-first-team	U16-U19

Note: RIEA: repeated intense exercise ability; IAT: individual anaerobic threshold; included teams: describes which teams contribute to the sample of each correlation, for example, U13-first team indicates all teams starting from U13 up to the first team (U13,14,15,16,17,19,23, first team); boldface numbers highlighting CIs not including zero.

with 30-m acceleration was reversed to a negative small to moderate correlation after controlling for the age group (see Table 3).

3.5 | Noncontact injuries

Small to moderate correlations with noncontact injuries ($n = 22$) were present for WMC, inhibition, countermovement jump and squat jump. None of these correlations remained meaningful after controlling for the age group whereas 30-m acceleration showed a moderate to large and performance-IAT showed a negative small to moderate correlation (see Table 3).

4 | DISCUSSION

The identification of key characteristics of talent is a crucial facet of domains in which humans need to thrive to high-performance in complex settings. Elite soccer is one of these settings where cognitive and physiological abilities are essential properties of the game whereas evidence on the contribution of multidisciplinary performance data is scarce.

Regarding the primary aim of the study, the present data indicate for the first time that better performance of executive functions (objective and coach-rated) is associated with an objective rating of successful soccer performance, that is, game time, across all included ages (i.e., 12–34 years). More specifically, coach-rated game intelligence and CF represent moderate to large correlations with game time and WMC, cognition score and selective attention show small to moderate correlations with game time. As only inhibition showed no meaningful correlation the first hypothesis can be partially proved. These findings are in line with previous results on the interrelation of executive functions and superior performance in elite athletes (Scharfen & Memmert, 2019a) and moderate effect sizes regarding success in soccer as measured by scored goals, assists (Vestberg et al., 2012, 2017, 2020) and the acceptance into an elite soccer academy (Sakamoto et al., 2018), which only reported small effect sizes. These previous associations of executive functions with success in elite soccer partially rely on the design fluency tests which measures higher-level executive functions planning and problem-solving (sometimes called fluid intelligence; Diamond, 2013) including creativity, response inhibition, working memory and CF (Sakamoto et al., 2018; Vestberg et al., 2017). Thus, the difference to the executive function tests used in the present study lays in the isolated measure of core executive functions compared to the combined analysis of higher-level executive functions. Although, the design fluency test has been suggested to simulate the executive decision-making chain similarly as in a real soccer situation (Vestberg et al., 2017) the core components CF and working memory have been indicated to be the main driver of the associations with success which may be confirmed by the present results. While the strength of the design fluency test is the higher ecologically validity, the weakness which is simultaneously the strength of the isolated tests is the clear distinction which core executive functions drive a certain association.

But as an important extension, this evidence might also be enlarged as the measure of success in the present study may also be even more valid since game time is commonly used (Rumbold et al., 2020) as it is achievable for players of all positions compared to goals and assists, which is more challenging to realize for defenders compared to strikers. Similar to the correlation with game intelligence, it is remarkable that the unique relationship between executive functions and game time seems to exist across all teams as age had no meaningful effect on the correlation. Again, this could hint at a central association integral to soccer expertise at all developmental phases from age 12 up which may support both, the nature as well as the nurture hypothesis. Thus, these findings along with the relationship of game intelligence and executive functions across all age groups may be used as valuable insights into the current demands of high-performance in complex team sports like soccer as a kind of performance-needs analysis (Baker et al., 2020). More specifically, the exploratory youth-adult subgroup analysis showed that these demands may differ among youth and adult elite soccer as all cognitive and both acceleration parameters present small to moderate effect sizes in the youth group (except for inhibition) whereas only working memory, CF but contrary also inhibition were meaningfully associated with game time in the adult group. However, the fact that inhibition in the youth subgroup was not associated with game time contrasts with prior studies suggesting the importance of inhibition for soccer players with small effect sizes (Verburgh et al., 2014, 2016).

Additionally, the findings enlarge the current understanding of the cognitive and physiological association with expertise and talent in certain developmental stages (Baker et al., 2019, 2020; Johnston et al., 2018; Till & Baker, 2020).

Moreover, a key question is whether executive functions develop due to systematic exposure to high quantities and qualities of training (i.e., nurture) or whether this is a prerequisite to play on an elite level (i.e., nature). Recent findings of a large longitudinal study of elite soccer players question the nurture approach (Beavan et al., 2020). Although the present results are not inferential and cannot resolve that debate, they may suggest that executive functions have a substantial relation to game intelligence and game time representing essential performance parameters of the soccer game. As an important extension to previous findings and contrary to Beavan et al. (2020), these associations are already present in the youngest age group possibly hinting at a low probability that this is solely based on nurture but rather on a selection phenomenon (nature hypothesis) (Sakamoto et al., 2018) as younger children have not yet gained a long experience of soccer training. However, the difference in the applied executive function tests (e.g., no working memory or CF test in Beavan et al., 2020) and age groups (i.e., no adult elite team in Beavan et al., 2020) need to be considered which probably also contributes to the differing findings.

Conversely, children in the age of 12–13 years of age playing for a professional soccer club probably have a history of several years of continual movement and motor experience which also boosts executive functions (Cox et al., 2016; Prakash et al., 2015). Thus, the nature as well as the nurture hypothesis might be supported by the present findings.

Furthermore, the results of the physiological performance data show that the covariate age had a considerable effect on the interactions of the physiological parameters RIEA and sprint with game time which could be explained by the fact that younger players' physiological capabilities are less developed compared to older players resulting in slower sprint times and lower endurance performance. By eliminating this age effect through partial correlation analysis, the underlying substantial association became noticeable. More specifically, the abilities RIEA and sprint (5 and 30-m time) were correlated on a moderate level with game time, confirming similar results of moderate effects of a previous review (Murr, Raabe, & Höner, 2018) concerning their relation to success (i.e., the entrance to the next development stage of an elite youth academy). Thus, the first hypothesis can only be partially confirmed. This association seems intuitive as these skills are constantly mentioned as important performance indicators in soccer (Oone et al., 2012; Reilly et al., 2000). However, small differences between the current RIEA and endurance tests included in the review cannot be excluded and should therefore be considered.

None of the other physiological parameters showed meaningful associations and only negligibly effect sizes—except for drop jump and performance-IAT trends showing small effect sizes, which is contrary to moderate effect sizes of prior review evidence (Murr, Raabe, & Höner, 2018) and our hypothesis.

Consequently, the present results suggest that mainly the executive functions (except for inhibition) along with the physiological abilities sprint and RIEA (only in the youth subgroup) contribute meaningfully to the game time of elite soccer players. As an essential addition, the current findings may partially answer the question of Beavan et al. (2020) in terms of the association of domain-generic executive functions and success in elite soccer. However, the smaller sample sizes of the physiological parameters RIEA, squat jump and performance-IAT compared to the cognitive parameters also need to be considered.

The secondary aim of this study was to analyze the extent to which the multidisciplinary performance data are associated with injuries. Concerning contact injuries, only the 30-m sprint represents a meaningful negative correlation with contact injuries (i.e., small to moderate). The covariate age influenced this correlation (i.e., switching substantially from positive to negative), which may again be explained by the fact that the youngest teams (i.e., U13-U15) are slower than their older peers based on their developmental phase. As players of this age group sustained no injury at all, this incidence distorted the primary bivariate correlation before controlling for age. However, this counterintuitive result proposing that physically faster players sustain more contact injuries is not in agreement with previous literature suggesting that better sprint performance reduces the injury risk (Malone et al., 2018) in adult elite soccer players and contradicts our fourth hypothesis. Yet, it is unclear whether the relationship of the study (Malone et al., 2018) mentioned above is evident in all types of injuries (i.e., contact vs. non-contact). One could argue that faster players could have more duels and therefore contacts with other players resulting in an increased probability to sustain an injury. As 92% of the contact injuries are related to the lower limbs (see Appendix 6), this might indicate that the possible higher velocities of faster players may intensify the impact of those duel-contacts with opposing players and therefore increase the injury risk.

Additionally, the higher mechanical load in faster players could also contribute to this heightened risk (Beato & Drust, 2020). Nevertheless, this is somewhat speculative as this association is the first of its kind to our knowledge. It also needs to be considered that no contact injuries occurred in the age groups U13-U15.

Moreover, although previous literature suggests that executive functions are related to injuries with moderate to large effect sizes (Swanik et al., 2007) and injury-risks (Giesche et al., 2020; Monfort et al., 2019), no meaningful correlation with contact- and non-contact injuries were observed in the present study, contrary to our second hypothesis. However, the different study designs of the previous investigations, including amateur athletes of various sports with predominantly controlled injury testing situations, may also explain this discrepancy. The current study analyzed the relationship between multidisciplinary performance data and elite athletes' injuries for the first time.

Regarding the second injury classification, "non-contact," a moderate to large correlation of sprint (30-m) was present, indicating a lower non-contact injury incidence in faster players. This confirms previous studies indicating a lower injury risk in athletes with higher speed (Malone et al., 2018, 2019) and partially our hypothesis. 50% of all non-contact injuries (see Appendix 6) are related to musculature, which is in line with previous studies suggesting that well-developed sprinting-related muscles reduce the injury risk (Malone et al., 2018, 2019). However, as a crucial expansion, present findings also show that the player's developmental phase influences this relationship.

Lastly, performance-IAT was negatively and small to moderately correlated with non-contact injuries suggesting that players with better anaerobic endurance performance are less likely to sustain a non-contact injury. Fatigue results in a higher injury risk based on lower coordination performance, among other factors due to decreased neuromuscular control (Huygaerts et al., 2020). Thus, as players with a better performance at the IAT get fatigued later, their injury risk may be reduced. Further, this association is also in line with the protective function of a well-developed cardiovascular and musculoskeletal system (Gabbett, 2016). Again, the covariate age had a meaningful effect on both associations, similar to the contact injuries. However, the smaller sample size and the fact that the performance-IAT parameter was only present for the teams U16-U19 need to be considered.

The third, exploratory hypothesis of study can be confirmed by the present results for the most part and propose that coach-rated game intelligence correlates small to moderately with the executive functions working memory and CF. In contrast, selective attention and inhibition had no relation with game intelligence. In agreement with the current investigation, a previous study (Vestberg et al., 2020) found a moderate correlation of coach-rated game intelligence with design fluency, a test combining all three executive functions. The correlation of that study was slightly smaller than that of the present investigation ($r = 0.37$; 0.42, respectively) which could be based on the sample size twice as large in the current study. Even more importantly, for the first time, the present study not only shows this relationship in adults but also in adolescents and children. Specifically, the current association seems to be present across all developmental stages (i.e., all tested age groups) as age had no meaningful effect on the correlation. This might significantly expand the findings of adult players and point at a fundamental linkage inherent to the soccer expertise at all included phases of age.

Further, it was proposed that specifically CF may contribute to game intelligence, which can be confirmed based on the present findings. Contrary to the current results, no correlation between game intelligence and working memory was found in the aforementioned study (Vestberg et al., 2020). This could be based on the difference in the applied working memory test which was a one-back working memory test with a subversion including a variable n-back in which the subject has to respond if he or she has seen a displayed card any time earlier in the test sequences. Although, these n-back versions are valid tests they may not depict the ecologically valid demands of the dynamic and complex soccer game on the working memory system. On the other hand, the counting span working memory task applied in the present study required the participant to count randomly arranged, specific shapes among distractors and afterward remembering the count totals for later recall. After the presentation of 2–7 images a recall mask occurred into which the participant had to fill their memorized count totals in the exact order they had been illustrated in. However, when also considering the superiority of working memory in elite soccer players evident in previous studies (Vestberg et al., 2012, 2017), the results altogether suggest an importance of working memory for successful soccer behavior in youth as well as adult players.

Thus, especially CF and WMC seem to be associated with game intelligence.

Limitations of the current study should also be acknowledged. Although multidisciplinary performance data were used, it still does not capture the complexity of a team sport like soccer holistically as technical/tactical skills and psychological abilities (e.g., resilience) are missing which have been reported as important properties (Formenti et al., 2020; Gabbett et al., 2007). Additionally, while current research indicates that the included performance parameters are important properties of elite soccer, it is still possible that other parameters which were not analyzed may also contribute essentially to success in elite soccer. Lastly, due to the partially differing sample sizes contributing to the individual parameters (i.e., RIEA, IAT, SJ) these associations, of course, have a smaller precision and power to detect effects if they exist compared to those with a larger sample size >100. Specifically, the precision of the confidence interval and the likelihood of the correlation of game time with working memory and CF ($n = 128$) revealing the actual and representative value is much higher than the precision of the correlation of performance-IAT with game time ($n = 42$). Thus, the interpretation of the correlations with the three parameters RIEA, performance-IAT and SJ could be a little biased compared to all other parameters which include a sample size of more than 100 players. Consequently, this potentially skewed demonstration of the actual population value always needs to be considered in the interpretation of the present findings. Thus, it should not be inferred that the effect of cognitive functions on game time is generally larger than the effect of the performance-IAT but rather that the likelihood of this larger effect is just bigger based on the larger sample size. Taken together, one should interpret the findings with different evidence levels. Specifically, the parameters with a sample size of >100 and <100 may represent evidence levels A and B, respectively. However, future research needs to confirm this likelihood in studies with equal sample sizes for both parameters. This also leads to differing injury numbers as not all parameters are present for each team resulting in not considering injuries of that specific team where no data are available (e.g., for IAT). Furthermore, no control group of fitness and age matched or female athletes were included which could be an important aspect of future research.

In total, the age-independent and fundamental associations of executive functions with game intelligence and game time may extend previous findings and their importance for elite soccer expertise at all ages besides providing insights into current demands of high-performance in complex team sports like soccer as a performance-needs analysis (Baker et al., 2019). Thus, future research should further research possibilities to enhance these executive functions as current training tools seem to evoke very limited transfer (Scharfen & Memmert, 2021). Further, the applied, unique multidisciplinary approach also highlights the crucial role of specific physiological abilities for success in soccer regarding game time and age-dependent injury avoidance. Future studies should also include technical/ tactical as well as psychological (i.e., resilience) skills to create a holistic approach to talent identification and the endeavor to track their future success. Moreover, more sophisticated parameters are needed to capture the multifaceted construct of success in a dynamic and complex setting like elite soccer (Memmert & Raabe, 2018).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

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