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Analysis of cognitive abilities measured in a laboratory-controlled 360° simulation in soccer

Introduction

Soccer is the most popular spectator sport in the world (Bandyopadhyay, 2017). According to Fédération Internationale de Football Association (FIFA), in which 187 countries are considered, there are at least 128,983 professional soccer players worldwide (FIFA, 2019). Soccer is the most extensively researched team sport (Reilly, Bangsbo, & Franks, 2000). Research in the field of soccer is based on match analysis (Hudges & Franks, 2007), physiological demands of players during training and match play (Reilly et al., 2000; Dodd & Newans, 2018) the typical injuries of soccer players (e.g., Ekstrand, Hägglund, & Waldén, 2011).

Soccer is a complex sport, requiring the repetition of many perceptual, cognitive, and motor processes. Several tests are currently being used to assess players' physical prowess (Rampinini, Coutts, Castagna, Sassi, & Impellizzeri, 2007). For instance, aerobic capacity can be assessed using the Yo-Yo test (Krustrup et al., 2003), simple running tests can be used to monitor speed, agility, and repeated sprint performance, and countermovement jumps can be used to assess leg power (for more information see the reviews by Reilly & Doran, 2003; Bangsbo, Iaia, & Krustrup, 2008). Nevertheless, it is remarkable that there is an absence of studies on skill performance (Russell & Kingsley, 2011) within the research literature. However, it is widely acknowledged that the successful execution of skill is the most essential aspect of soccer play. When players' fitness is monitored in such studies, the assessment of cognitive abilities is also rarely included.

The kinematics of team sports have changed significantly over the past ten years. On the one hand, sports players move faster on average (Soccer; Wallace & Norton, 2014), cover greater distances (Barnes, Archer, Hogg, Bush, & Bradley, 2014), and have more frequent sprints per game. The total distance covered in a soccer match of 90 min in 2006 was approximately 2% less than in 2012/2013 (Barnes et al., 2014). On the other hand, the increase in speed relates to the ball, shown by the shorter possession time of players and the increased number of ball contacts (Wallace & Norton, 2014). The shorter but more frequent ball contacts require sports players to make more decisions in a short period. As a result of the factors mentioned above, the modern sports player needs improved training possibilities concerning cognitive functions. Also, German national coach Joachim Löw concluded a lack of cognitive functions after dropping out of the World Cup in 2018 (Kramer, 2018). Significant potential lies in searching for the development and promotion of the players' relevant cognitive skills and abilities (Söhnlein & Borgmann, 2018).

Research in the field of cognitive functions in team sports pursues two differentiated approaches concerning the description and prognosis of perceptual-cognitive performance. The first and most commonly used theory is based on the Expert-Performance Approach (Williams, Ericsson, & Anders, 2005). In association with the theory, comparisons are made between experts and novices in a sport-specific context (test for decision-making behavior; Williams & Ward, 2007). The experts show better performance concerning the sport-specific requirements for cognition (pattern recognition; e.g., Abernethy, Baker, & Côté, 2005), perception (visual search strategies; Vaeyens, Lenoir, Williams, Mazyn, & Philippaerts, 2007) and decision-making behavior (Williams & Ward, 2007; Weigel, Raab, & Wollny, 2015). The quality of tactical decision-making is evaluated by experts (Hepler & Feltz, 2012). When examining the decision-making actions and the ability to anticipate movements of the opponents, the eye movements of the participants are tracked by eye-tracking glasses in addition to the evaluation of the quality of decision (Kredel, Vater, Klostermann, & Hossner, 2017). The studies using an expert performance approach analyze the athletes under sport-specific or ecologically valid contexts (Mann, Williams, Ward, & Janelle, 2007; Starkes & Ericsson, 2003).

Compared to the Expert-Performance Approach, the Cognitive-Skills Approach examines the extent to which the sport-specific cognitive abilities are based on basic cognitive and perceptual functions (Montuori et al., 2019). Inhibition, working memory, and cognitive flexibility are examples of executive functions (Alves et al., 2013; Diamond, 2013). They act as a requirement for higher-level executive functions (e.g., reasoning) or other cognitive functions such as anticipation (Diamond, 2013). Inhibition or inhibitory control is the ability to control or inhibit impulsive (or automatic) responses to stimuli, especially to irrelevant information, or suppress an ongoing motor action (Verburgh, Scherder, van Lange, & Oosterlaan, 2014). Working memory can be described as the process of storing information that can be temporarily maintained in an accessible state, making it useful for cognitive tasks (Furley & Memmert, 2012). Cognitive flexibility can be broadly defined as the ability to adapt behaviors in response to changes in the environment. Inhibition, working memory, and cognitive flexibility are relevant in team sports situations. If a player wants to pass the ball to a teammate and an opponent covers the passing line, the player has to suppress this motor action to adapt it to the game situation changes. The executive functions can be quantified by simple computer tests (e.g., Vienna Test System).

Some researchers postulate the hypothesis that perception and action emerge from individuals' experience with environmental constraints over time towards specific behavioral goals (Seifert, Button, & Davids, 2013). This approach developed from the field of ecological psychology. With the increasing knowledge of the task's requirements, experts use different perception variables to be able to ensure enhanced attention on the more effective stimuli under the affordances. "In contrast, novices tend to pick up and use sources of information that may be only partially functional in particular performance situations because they do not specify actions effectively" (Seifert et al., 2013, p. 170). The cognitive function of anticipating movements is the only example of a higher cognitive function measured in the test battery. The anticipation of an upcoming movement of an opponent is strongly connected with pattern recognition in sports, and it is a key factor in performance in team sports. In the present study, the requirements in the form of the stimuli were designed to be non-specific (e.g., react to a flashing red field in Choice Reaction test) and the movement that must be carried out in response to the stimuli was designed domain-specific (soccer: to shoot the ball).

We postulate that cognitive tests are determined by age, development of appropriate central nervous structures, and the experiences with unspecific task affordances.

Furthermore, age is often neglected when considering cognitive functions. Some authors (Stuss, 2011) describe a significant relationship between age and cognitive function development. Executive functions (EF) depend on prefrontal structures, which are likely to be fully developed between 23 and 26 years of age (De Luca et al., 2003; Gogtay et al., 2004). Results in neuroscience could prove this relationship: "Extensive neuroimaging research in adults has revealed that the lateral prefrontal cortex plays an important role in EF" (Moriguchi & Hiraki, 2013). Cognitive or executive functions such as attention control, processing speed, cognitive flexibility, goal setting, inhibitory ability, and working memory mature through late childhood until puberty and are fully developed at around 19 years of age (Huizinga, Dolan, & van der Molen, 2006). The strategic planning and the organization of goal-directed behavior seem to be fully developed between the ages of 20 and 29 (De Luca et al., 2003). Zhan et al. (2020) proved that children with higher levels of cardiorespiratory fitness and children of a higher age are generally associated with advanced working memory inhibitory control and shifting aspects of executive functions. Older soccer players should outperform younger players with less developed prefrontal structures and less experience in perceiving relevant information. Beavan et al. (2020) showed more variation in the period between the ages of 10 and 15.

Currently, several studies focus on the connections between the different higher cognitive functions (e.g., anticipation) and the measurement of the executive functions in a sporting context (Awh, Vogel, & Oh, 2006; Furley & Memmert, 2012). For example, working memory is structurally connected with attention. Awh et al. (2006) describe that "attention can serve as a kind of 'gatekeeper' for working memory, by biasing the encoding of information toward the items that are most relevant to the current processing goals". Miyake et al. (2000) describe a confirmatory factor analysis on the relations between the three target executive functions, which indicated that they are moderately correlated with one another but are separable. According to the equation modeling, the authors postulate that the three executive functions contribute in different manners to the performance on complex executive tasks (Miyake et al., 2000). The results of a study by Nakamoto and Mori (2012) suggest that fast-ball athletes can reduce anticipation timing cost by developing inhibitory control. These results could verify the structural connection between inhibition and anticipation processes. It is assumed that the constructs described also influence one another or correlate in the present study.

Modern sports science demands adequate measurability of cognitive abilities in sports games and the development of new training methods to improve such abilities. Recent developments in technology, like the 360° simulation for the application of sport-specific cognitive training and cognitive testing (SoccerBot360, Umbrella Software Development GmbH or SAP Helix 180, SAP Deutschland SE & Co. KG) lead to advanced knowledge in the analysis of tactical decisions, sport-specific cognitive abilities (anticipation, pattern recognition, attention) and executive functions (working memory, inhibition, cognitive flexibility). Some authors were able to prove a difference in executive functions between athletes of different sports (Jacobson & Matthaeus, 2014; Krenn, Finkenzeller, Würth, & Amesberger, 2018; Gu, Zou, Loprinzi, Quan, & Huang, 2019) or different expertise levels (Kioumourtzoglou, Derri, Tzetzis, & Theodorakis, 1998; Vestberg, Gustafson, Maurex, Ingvar, & Petrovic, 2012). Based on the results of their meta-analysis, Scharfen and Memmert (2019) concluded that it could be beneficial for coaches and sports clubs to integrate cognitive tests as an additional tool for scouting and to optimize the athletic development of their players.

Vestberg et al. (2012) even postulate that executive functions can predict the success of top soccer players.

The aim of this study was to quantify the executive functions and anticipation abilities (choice reaction, inhibition, working memory, anticipation) in youth soccer players in a laboratory-controlled setting using a 360° simulation. The training and diagnostic tool offers soccer players the opportunity to conduct special e-trainings and realistic tactical decision-making training in a virtual 360° room. The players can interact with the projection surface as an action in the game by shooting or passing the ball against the screen and triggering corresponding reactions (trajectory with direction and speed is simulated).

The results of the study may provide information concerning the training and diagnostic possibility of cognitive abilities of soccer players in a 360° simulation while simultaneously considering the age of the participants. In addition to that, this paper deals with the question of whether these cognitive abilities of different complexity (choice reaction, working memory, inhibition, and anticipation) may be connected.

Materials and methods

Participants

A total of 82 male youth soccer players were examined (age: 11–17 years; 4 teams in age groups: under 12 years [U12; $n=24$], under 13 years [U13; $n=18$], under 14 years [U14; $n=18$] and under 17 years [U17; $n=22$]). The focus in this study was on young soccer players at the age of 11–17 years because Beavan et al. (2020) showed that "within high-level athletes, large improvements apparent between the ages of 10–15 and steady yet considerably smaller performance improvements observed throughout adolescence and into early adulthood". At the time of the study, all soccer players are involved in the youth academy's talent development program of a professional soccer club (first division). Soccer players at the youth academy can be classified as highly talented players because the coaches and scouts make preselections concerning soccer-specific qualities such as technique, tactics, and athletic skills on a regular basis. The study design does not take into account a control group due to ethical and organizational issues. The youth academy gives every player the opportunity to train in the 360° simulation. Due to the lack of a control group, the results must be discussed even more critically.

Measures

Equipment

The circular training device used in the study has a diameter of 10 m, which offers a 90 m^2 inside playing field (artificial turf). The playing area's surface is formed by 32 segments (1 m × 2.5 m), which also serve as a projection surface for the training content and can be hit by the ball. The surface area consists of 80 m^2 and a 360° projection surface, which makes it possible to show the player real-time rendered three-dimensional content in full high-definition (HD) resolution. The built-in high-speed infrared camera (120 Hz) determines how fast, at which location on the 360° projection surface and with which foot one or more players pass or shot the ball. In addition to this, the ball processing time and the respective foot of the ball receiving are recorded (**Fig. 1**).

Test battery

In the study on the analysis of cognitive abilities in laboratory-controlled 360° simulations, participants had to absolve modified neuropsychological tests for the SoccerBot360, which indicate the participants' performance concerning inhibition, working memory, anticipation, and choice reaction. The test battery includes five different test items (Stroop number test, Corsi Block test, two Anticipation tests, and a Choice Reaction test) to evaluate the cognitive abilities of soccer players. In their original form, the tests used have good validity and reliability. There is still no knowledge of the test quality criteria for the modified form for use in the 360° simulation. The modified tests are evaluated concerning their ability to differentiate between subjects and age groups. Still, they are not examined to describe their performance concerning quality criteria.

The Choice Reaction test (Vänttinen, Blomqvist, Luhtanen, & Häkkinen, 2010; processing speed) was implemented because the study should examine the relationship between processing speed and executive functions of the soccer players. Players had to shoot the ball on the goal on the projection, which appears with a red background. Albinet, Boucard, Bouquet and Audiffren (2012) were able to show that measurements of processing speed and executive functions share mutual variance. However, each measurement was influenced regardless

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Abstract
Soccer, which is characterized by a very high pace and a short possession time, requires players who are well trained in cognitive abilities. The aim of the study was to quantify cognitive abilities and the improvements in cognitive measures in a laboratory-controlled 360° simulation setting. In all, 82 male youth soccer players (4 age groups) were examined with a pre-/posttest design with an e-training intervention in a unique 360° simulation tool (SoccerBot360 [Umbrella Software Development GmbH, Leipzig, Germany]). The cognitive abilities, especially executive functions, were measured using cognitive tests (Stroop number test, Corsi Block test, Anticipation tests, Choice Reaction test) modified for the 360° simulation to evaluate executive functions and anticipation. The analyzed soccer players showed significant positive changes in cognitive tests from pre- to posttest and significant group effects. The changes in the cognitive test values are not exclusively due to the additional training in the simulation. Nevertheless, the results show significant differences between the four age groups in cognitive abilities and their development.

Keywords
Cognitive functions · Executive functions · Prefrontal structures · Virtual reality · Soccer

Fig. 1 ▲ The 360° simulator (SoccerBot360)

Fig. 2 ▲ Training game mode in the SoccerBot360 (Umbrella Software Development GmbH, Leipzig)

of chronological age. They show that the processing speed theory and the prefrontal-executive theory are not mutually exclusive but share mutual variance. Processing speed is a relevant factor in soccer because a fast processing speed leads to fast decisions.

The Stroop number test (relation to standard Stroop Effect; carried out by Vestberg et al., 2012) shows the relationship between numerical values and physical sizes. The Stroop number test examines the participants' ability to inhibit irrelevant information in stimuli presentation (size of digit). Besner and Coltheart (1979) asked their participants to point to the number with the higher or lower value and ignore the digits' sizes. The Stroop Number test was adapted to the SoccerBot360 (◘ **Fig. 2**). The participant did not press a key to react to a stimulus, but with the ball that is to be shot close to the correct number. There were 20 trials in total (10 times lower value, 10 times higher value). The reaction time for two types of stimuli were measured: high value—large font size (congruent), low value—large font size (incongruent). Advanced inhibition control or the ability to suppress an ongoing motor action is relevant for high performance in soccer players (Verburgh et al., 2014). The Corsi Block test (Corsi, 1972) quantifies the ability to memorize the order of squares that change color one after the other and describes the participants' working memory. In the SoccerBot360, a yellow arrow marks several pylons (10 on the field at 360° around the player), which had to be hit with a ball in the specified order (◘ **Fig. 3**). If the order is correct, a new order with an additional pylon was presented. If the participant failed, the same number of pylons was shown. After three successive errors, the test ended, and the highest number of successfully memorized pylons was stored as the measured value (Alves et al., 2013; Furley & Memmert, 2010). The results on the connection between high performance and adequate decision-making in soccer are inconsistent. Nevertheless, a test should be carried out for working memory to uncover possible connections between EFs.

Furthermore, two Anticipation tests were carried out: with and without time pressure. The tests were carried out to find possible connections between executive functions and higher cognitive functions such as visiospatial anticipation. In the first test (under time pressure), the players had to follow a diagonally falling ball and pass the ball to the location where the falling ball hits the ground. Time pressure for the pass was generated via sound, so the players had to anticipate the point of impact very early. There were 12 trials, and the horizontal distance is recorded for every trial. The second Anticipation test (without time pressure) showed diagonally falling balls (two to three balls simultaneously). All the balls stop halfway. The participants had to anticipate where every ball hits the ground. In summary, there are 15 falling balls in six trials. The horizontal distance is recorded for every item (ball). Skill execution (accuracy of shot) was neglected concerning the test result. Good accuracy in shooting a ball is being expected for the players. The influence of the skill cannot be controlled in this case.

Design and treatment

The cognitive abilities were tested in a pre–post design using modified cognitive tests of the 360° simulator (SoccerBot360, described in the prior section). The soccer players completed a 12-month training period in the virtual 360° setting (1–2 training units per week) in addition to their regular training in the youth academy. The training was a challenging cognitive-motor-driven e-training to improve cognitive abilities (in addition to the standard training units). One of the training modes of the 360° simulator is shown in ◘ **Fig. 2**. The game pieces (targets) displayed several times on the top edge of the 360° screen, which must be detected, searched for in the entire projection, and then hit with the ball. The player receives a point for correctly hit pieces (additional points for the right color). The currently displayed game piece and the next three game pieces to be hit are displayed as a preview. It should be made clear that the training sessions do not represent realistic or laboratory-controlled game situations.

Statistical analysis

To analyze the development of the participants' cognitive abilities from pre- to posttest, changes in the entire sample and

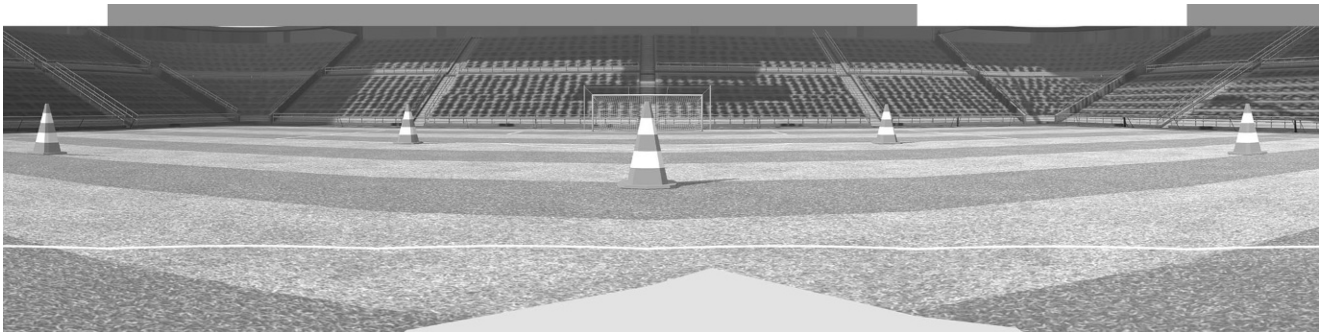

Fig. 3 ▲ Projection of the modified Corsi Block test in the SoccerBot360

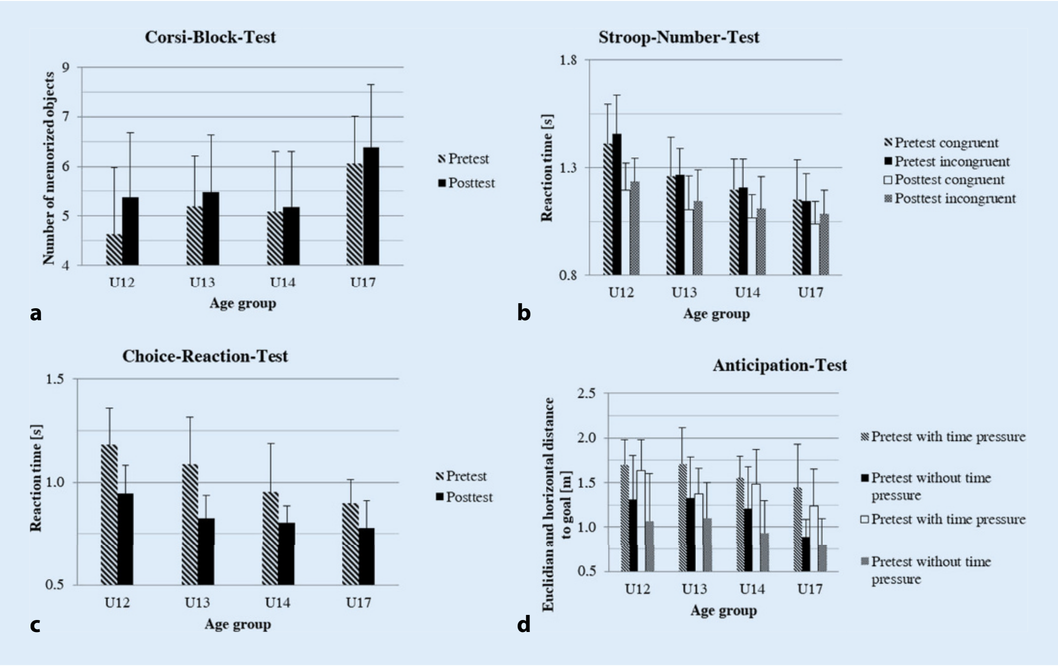

Fig. 4 ◀ Results of the modified Corsi block test (**a**), Choice reaction test (**b**), the modified Stroop Number test (**c**) and Anticipation test (**d**) for the two measurements and four age groups (U12, U13, U14, U17) and the congruent and incongruent stimulus presentation with and without time pressure

the individual groups were shown. The differences between the age groups relate to the age-dependency of cognitive abilities. The correlations between the single test items describe whether and to what extent the single constructs of executive and cognitive abilities (inhibition, working memory, choice reaction, anticipation) are connected.

The statistical calculations were executed using the IBM SPSS Statistics 25 software (International Business Machines Corporation, New York, NY, USA). A Shapiro–Wilk test was calculated to check the normal distribution of variables. Values for eight out of 14 variables were not normally distributed. Due to the non-normal distribution of the data, non-parametric tests were calculated to evaluate the differences and correlations. Differences within and between the groups were calculated using the Wilcoxon test and Kruskal–Wallis test (posthoc: Mann–Whitney-U test; α corrected with Bonferroni). The correlations between the tests are verified using the Spearman-Rho correlation coefficient with the suggested interpretation of Nachtigall and Wirtz (2004): $0.50 = $ low, $0.70 = $ moderate, and $0.90 = $ high.

Results

Within-subject effects

The 82 youth soccer players show significant improvements from pre- to posttest in four out of five cognitive tests (*Wilcoxon test: Stroop Number test:* $Z = -7.41$, $p < 0.001$; *Corsi Block test:* $Z = -2.55$, $p = 0.011$; *Anticipation test [without time pressure]:* $Z = -3.88$, $p < 0.001$; *Choice Reaction test:* $Z = -7.55$, $p < 0.001$; see **Fig. 4**). There were no significant differences between pre- and posttest for the Anticipation test under time pressure ($Z = -1.63$, $p = 0.104$).

There are significant differences within the four groups (U12, U13, U14, U17) in reaction time for the Stroop Number test from pre- to posttest (*U12:* $Z = -4.26$, $p < 0.001$; *U13:* $Z = -3.55$, $p < 0.001$; *U14:* $Z = -3.42$, $p = 0.001$; *U17:* $Z = -3.58$, $p < 0.001$). In the Corsi Block test only the values of the group of under 12 year old soccer players differs significantly from pre- to posttest (*U12:* $Z = -2.24$, $p = 0.025$; *U13:* $Z = -0.98$, $p = 0.329$; *U14:* $Z = -0.32$, $p = 0.747$; *U17:* $Z = -1.92$, $p = 0.225$). The post hoc tests

Table 1 Spearman Rho correlations between cognitive tests for the pretest (posttest)

Spearman Rho correlation of cognitive tests	Choice Reaction test	Anticipation test (no time pressure)	Anticipation test (time pressure)	Stroop Number test (congruent)	Stroop Number test (incongruent)
Corsi Block test	-0.239^{*} (-0.153)	-0.119 (-0.097)	-0.098 (-0.231^{*})	-0.349^{**} (-0.204)	-0.335^{**} (-0.048)
Choice Reaction test	–	0.251 (0.260^{*})	0.308^{**} (0.122)	*0.696^{**}* *(0.738^{**})*	*0.751^{**}* *(0.631^{**})*
Anticipation test (no time pressure)	–	–	0.093 (0.232)	0.137 (0.132)	0.265^{*} (0.172)
Anticipation test (time pressure)	–	–	–	0.266^{*} (0.033)	0.271^{*} (0.050)
Stroop Number test (congruent)	–	–	–	–	*0.910^{**}* *(0.696^{**})*

$^{*}p < 0.05$, $^{**}p < 0.01$

do not show differences between pre- and posttest for the Anticipation test under time pressure (*U12:* $Z = -0.78$, $p = 0.433$; *U13:* $Z = -1.78$, $p = 0.075$; *U14:* $Z = -0.56$, $p = 0.575$; *U17:* $Z = -0.91$, $p = 0.363$). In contrast, there is a difference within the age group U14 between the two measurement points of anticipation without time pressure (*U12:* $Z = -1.77$, $p = 0.076$; *U13:* $Z = -1.46$, $p = 0.145$; *U14:* $Z = -2.59$, $p = 0.010$; *U17:* $Z = -2.38$, $p = 0.017$). In the Choice Reaction test, the age groups (U12, U13, U14, U17) improved significantly from pre- to posttest (*U12:* $Z = -4.29$, $p < 0.001$; *U13:* $Z = -3.72$, $p < 0.001$; *U14:* $Z = -2.85$, $p = 0.004$; *U17:* $Z = -3.95$, $p < 0.001$).

Between-subject effects

There are significant group effects for four out of the five cognitive tests at pretest (*Kruskal–Wallis test; Stroop Number test:* $H = 25.16$, $p < 0.001$; *Corsi Block test:* $H = 15.60$, $p < 0.001$; *Anticipation test [without time pressure]:* $H = 17.17$, $p < 0.001$; *Choice Reaction test:* $H = 32.32$, $p < 0.001$). No significant differences could be described for the Anticipation test executed under time pressure ($H = 7.21$, $p = 0.065$). There were significant differences in performance between the four age groups at the second measurement point for the Stroop Number test ($H = 16.63$, $p = 0.001$), the Corsi Block test ($H = 9.32$, $p = 0.025$), the Anticipation test (*under time pressure:* $H = 14.92$, $p = 0.002$) and the Choice Reaction test ($H = 23.26$, $p < 0.001$). No significant difference between groups in the anticipation without time pressure could be reported ($H = 7.78$, $p = 0.051$). The data on the differences between the individual groups (post hoc tests) are shown in the supplementary data.

Correlations between cognitive tests

The results of the bivariate correlation analysis for cognitive tests (▣ **Table 1**) show correlation coefficients between $r_s(82) = 0.030$, $p = 0.767$ *and* $r_s(82) = 0.910$, $p < 0.001$. The correlation between the reaction times for congruent and incongruent stimulus presentation (*pretest:* $r_s(82) = 0.910$, $p < 0.001$; *posttest:* $r_s(82) = 0.696$, $p < 0.001$) is characterized as moderate to high. The correlation between the reaction times of the Choice Reaction test and the Stroop Number test (*pretest:* $r_s(82) = 0.696$, $p < 0.001$ *[congruent]*, $r_s(82) = 0.751$, $p < 0.001$ *[incongruent]; posttest:* $r_s(82) = 0.738$, $p < 0.000$ *[congruent]*, $r_s(82) = 0.631$, $p < 0.001$ *[incongruent]*) can be described as low to moderate.

Discussion

The significant within-subject effects indicate different development stages of the participants concerning their cognitive abilities. As expected, the subjects of higher age performed significantly better in the cognitive tests (U12 < U13 < U15 < U17). The results are consistent with those of Vänttinen et al. (2010) and the results of Zhan et al. (2020). The hypothesis that cognitive tests are determined by age could be approved. The influence of the development of relevant central nervous structures (prefrontal structures, prefrontal cortex) and the experiences with unspecific task affordances could not be shown. For the description of the dependency of EFs on the development of central nervous structures, neuroimaging studies have to be conducted on this topic. The previous study results can expand knowledge about the determination of executive functions by age on the measure in a 360° simulation. The cognitive functions at this age are dependent on different prefrontal structures (Stuss, 2011). The prefrontal structures and cognitive functions are considered to be developed through late childhood to puberty and are fully developed at the age of about 23 to 26 years (De Luca et al., 2003; Gogtay et al., 2004). The cognitive functions are not fully evolved at the age at which the participants were examined, so development could be determined either by age or training in the 360° training tool. Further evidence for the hypothesis that the performance in cognitive tests depends on the development of prefrontal structures or cognitive development is provided by the fact that at the second measurement point, the groups performed comparably to the participants of the higher age group in the first test (▣ **Fig. 4**). Nevertheless, the measurement of cognitive skills under the use of the 360° simulation can differentiate between subjects of different ages. The cognitive tests' measured values can quantify the current level of development of the cognitive abilities and predict of the cognitive performance for the respective participant under soccer-specific conditions. The influence of training in the virtual setting on the process of cognitive development cannot be shown due to the lack of a control group. To examine the effects the performance of an intervention group had to be compared with a control group (without perceptual-cognitive intervention or with a different kind of training).

The use of e-trainings in a 360° simulation will not improve the soccer player's vision of the game, nor are the stimuli similar to soccer; there is no real match situation, neither teammates nor opponents. The improvement is limited to the tests of executive functions; adding to that, the improvement could not be attributed to the e-trainings because of age dependency. There may also be an effect of test repetition.

The hypothesis of Scharfen and Memmert (2019) that it could be beneficial for coaches and sports clubs to integrate cognitive tests as an additional tool for scouting and optimizing the athletic development of their players could be approved by the present results. The participants' current age-related performance concerning the executive functions can be determined using the test (except anticipation under time pressure).

The statement that the three target executive functions are moderately correlated with one another must be revised. The connections between higher cognitive functions (anticipation) and executive functions (Miyake et al., 2000) must be refused too. The results show low to moderate correlations between the cognitive functions. The low to moderate correlations between the reaction times in the Choice Reaction test and the Stroop Number test demonstrate the two tests' familiar variance, which is presumably given by the common property of having to choose quickly between two or three options. These correlations also validate the theory of Albinet et al. (2012) that measurements of processing speed and executive functions share mutual variance.

Overall, the significant positive changes in the cognitive tests performance cannot be entirely attributed to the e-training in the 360° simulation because the motor-cognitive development of the test subjects and the test repetition have influences on the change in test values from pre- to posttest. Nevertheless, the results show significant differences between the four age groups (U12 < U13 < U15 < U17) in cognitive abilities and the development of cognitive abilities over a period of one year. The test can possibly be used for talent identification and the general assessment of cognitive abilities.

Further research should focus on the validation of the modified tests (in 360° presentation). There is a lack of data on the validity and reliability of the conducted tests. A study with a control group is suggested to expand the results regarding the effectiveness of cognitive-motor training in a 360° simulation. The differences in skill execution should be considered when processing a new study design: control for differences or modulate the above-mentioned skill requirements. Further intensive investigations in moderator variables and mutual influences related to executive functions, and higher cognitive functions are considered useful.

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Declarations

Conflict of interest. F. Heilmann, P. Weigel and R. Wollny declare that they have no competing interests.

The study is conducted in accordance with the Declaration of Helsinki on Ethical Principles for Medical Research Involving Human Subjects, adopted by the General Assembly of the World Medical Association (1996).

Appendix

A. Supplemental data

Table 2 Mean reaction time (±SD) in [s], between and inner subject effects in Choice Reaction test for four age groups in pre- and posttest

Choice Reaction test	U12 (under 12 years)	U14 (under 14 years)	U15 (under 15 years)	U17 (under 17 years)	Between subject effects (*p*-value)
Pretest	1.18 (0.17)	1.09 (0.23)	0.95 (0.236)	0.90 (0.11)	0.000
Posttest	0.94 (0.14)	0.83 (0.11)	0.81 (0.081)	0.78 (0.13)	0.000
Inner subject effects (*p*-value)	0.000	0.000	0.004	0.000	–

Table 3 Mean memorized objects (±SD), between and inner subject effects in Corsi Block test for four age groups in pre- and posttest

Corsi Block test	U12 (under 12 years)	U14 (under 14 years)	U15 (under 15 years)	U17 (under 17 years)	Between subject effects (*p*-value)
Pretest	4.708 (1.513)	5.333 (1.155)	5.222 (1.359)	6.318 (1.061)	0.001
Posttest	5.542 (1.471)	5.667 (1.291)	5.333 (1.247)	6.682 (1.427)	0.025
Inner subject effects (*p*-value)	0.025	0.329	0.747	0.225	–

Table 4 Mean reaction time (±SD) in [s], between and inner subject effects in Stroop Number test for four age groups in pre- and posttest

Stroop Number test		U12 (under 12 years)	U14 (under 14 years)	U15 (under 15 years)	U17 (under 17 years)	Between subject effects (*p*-value)
Congruent	Pretest	1.360 (0.183)	1.210 (0.179)	1.148 (0.141)	1.102 (0.183)	0.000
	Posttest	1.147 (0.123)	1.055 (0.157)	1.017 (0.107)	0.989 (0.103)	0.001
	Inner subject Effects (*p*-value)	0.000	0.000	0.001	0.000	–
Incongruent	Pretest	1.406 (0.178)	1.219 (0.117)	1.157 (0.131)	1.096 (0.126)	0.001
	Posttest	1.184 (0.109)	1.096 (0.144)	1.060 (0.150)	1.036 (0.111)	0.000
	Inner subject Effects (*p*-value)	0.000	0.003	0.020	0.040	–

Table 5 Mean Euclidian or horizontal distance to the goal (±SD) in [m], between and inner subject effects in Anticipation test for four age groups in pre- and posttest

Anticipation test		**U12 (under 12 years)**	**U14 (under 14 years)**	**U15 (under 15 years)**	**U17 (under 17 years)**	**Between subject effects (*p*-value)**
Under time pressure	Pretest	1.704 (0.279)	1.706 (0.404)	1.554 (0.241)	1.445 (0.487)	0.065
	Posttest	1.636 (0.347)	1.377 (0.284)	1.484 (0.383)	1.242 (0.407)	0.002
	Inner subject Effects (*p*-value)	0.433	0.075	0.575	0.363	–
Without time pressure	Pretest	1.309 (0.490)	1.325 (0.463)	1.210 (0.462)	0.887 (0.204)	0.001
	Posttest	1.072 (0.526)	1.099 (0.399)	0.938 (0.362)	0.797 (0.296)	0.051
	Inner subject Effects (*p*-value)	0.076	0.145	0.010	0.017	–

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