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The impact of soccer-specific psychophysiological stress on inhibition and cognitive flexibility in elite youth players

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ABSTRACT

While researchers and practitioners attribute an essential role to executive functions (EFs) for soccer performance, the usefulness of respective diagnostics and the predictive value remain unclear. One limitation restricting the translation and relevance of study results to improve actual game performance is the insufficient consideration of competitive conditions. Thus, this study aimed to conduct soccer-specific cognitive diagnostics under a soccer-specific psychophysiological stress condition, mimicing the demands of a competitive game. A total of 92 (M_{age} = 15.17, SD_{age} = 1.45) youth elite players performed tests for inhibition (flanker task) or cognitive flexibility (number-letter task) with a soccer-specific motor response (i.e., pass into goals). After a pre-test in a neutral condition, players were randomly assigned to a neutral (moderate soccer-specific exercise) or a stress condition (physical stress and competitive instructions and filming for psychological stress). Objective (i.e., cortisol, heart rate variability) and subjective stress-related measures (i.e., SAM, VAS) were assessed six times throughout experimental procedure. Analyses revealed significant interaction effects between time and condition for all objective and subjective variables indicating a successful experimental stress induction. For cognitive performance, results revealed significant main effects of time, but no significant interaction effects between time and condition. However, descriptive statistics suggested improved performance under stress, with decreased flanker effect and switch costs. Additionally, response time variability in the flanker task significantly decreased in the stress condition. These findings offer insights into individual stress perception and processing under game-related psychophysiological demands, expanding previous research on situational EF alterations that also hold relevance for applied practitioners.

Prerequisites and skills to perform sports on high competitive levels are continuously debated in the context of talent identification and development, especially in soccer, due to the popularity of the sport and the resulting performance density in talented youth athletes (e.g., Huijgen et al., 2015). In addition to physical-motor and technical skills, there has been a growing emphasis on the significance of psychological and perceptual-cognitive skills (meta-analyses by Kalén et al., 2021; Voss, Kramer, Basak, Prakash, & Roberts, 2010). Based on a complex and multidimensional performance structure, cognition is ascribed to a potential role in the achievement and maintenance of peak performance in soccer (Murr, Feichtinger, Larkin, O'Connor, & Höner, 2018). Thus, the relevance of cognitive skills such as executive functions (EFs) has been emphasized. The core EFs –inhibition, cognitive flexibility, and working memory– are crucial for effective and goal-directed behavior (see reviews of Diamond, 2013; Miyake & Friedman, 2012). Based on their development during the stages of early and mid-adolescence (Huizinga, Dolan, & van der Molen, 2006), EFs are suggested to be related to expertise and motor skills in developing youth athletes

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(Marasso, Laborde, Bardaglio, & Raab, 2014; Scharfen & Memmert, 2019). However, it is unclear how EFs can be measured appropriately to enable conclusions for on-field performance (e.g., Van Maarseveen, Oudejans, Mann, & Savelsbergh, 2018). In this context, the question arises about the validity of assessing EFs under neutral conditions. The informative value of isolated EF assessments remains debatable, given that cognitive processes are constantly interconnected with psychological and physical demands, particularly evident in athletic performance (e.g., Walton, Keegan, Martin, & Hallock, 2018). During a competitive soccer game athletes are exposed to psychological and physiological environmental demands, also referred to as stressors, which trigger psychophysiological stress responses (Salvador & Costa, 2009; Thomas, 2009). It is assumed that both psychophysiological stress triggered by the high pressure of a competitive situation (e.g., Gaab, Rohleder, Nater, & Ehlert, 2005) and elicited by physical demands (e.g., Stølen, Chamari, Castagna, & Wisløff, 2005) influence performance (e.g., Fletcher, Hanton, & Mellalieu, 2008). However, the assessment of EFs under competitive conditions involving psychophysiological stress is often neglected in sports (Lautenbach, Putman, Angelidis, Laborde, & Raab, 2016). Yet, understanding how players cognitively adapt to pressure is both theoretically and practically important (Musculus, Raab, Belling, & Lobinger, 2018). Insights into this process, along with corresponding psychophysiological stressors, can yield conclusions about performance in competitive situations. Such findings could assist coaches and sports psychologists in developing targeted intervention strategies.

Accordingly, this study aims to understand the impact of soccer-specific psychophysiological stress on EFs (i.e., inhibition, cognitive flexibility) by simulating a game-related stress condition under which cognitive tasks are performed.

1. Stress and emotions

Stress has been defined as a multidimensional concept requiring research to consider a variety of measurements and constructs that provide insights into psychological and physiological adaptations (Skoluda et al., 2015).

Psychological stress is often closely related to other concepts such as affect, mood and emotions, which are relevant for competitive performance (e.g., Frame & Reichin, 2019). Affect is always present even though not continuously processed (Russell, 2003) and can be described on the two dimensions of valence (pleasant vs. unpleasant) and arousal (high vs. low). Emotions are characterized as short-term affective states elicited by a specific event associated with behavioral changes or certain action tendencies. According to Lazarus (2000, p. 231), “emotion encompasses all of the important phenomena of stress”, suggesting consideration as closely related concepts (see also Laborde, Raab, & Dosseville, 2013). An influential theory shaping our understanding of emotion generation across various contexts, including stressful situations, is the theory of constructed emotions by Feldman Barrett (2017a, 2017b). The theory opposes the view of emotions being fixed, universal responses to stimuli. Instead, it proposes emotions being constructed as an individual response to contextual information, past experiences, and knowledge (Barrett, 2017b). Therefore, the theory underscores a dynamic emergence of emotions, enabled by the brain’s flexible networking between the sensori information retrieved from the situation and from internal states (Barrett, 2017b; Fridman, Barrett, Wormwood, & Quigley, 2019). Concerning stress, it is assumed that individual differences in emotions result from physiological changes elicited by the current context and previously learned, individual patterns of stress responses (Barrett, 2017a; Fridman et al., 2019). Consistent with this, the way an individual appraises a situation directly influences the emotions they experience, thereby impacting athletic performance (Lazarus & Folkman, 1987; Tamminen & Bennett, 2017). Lastly, moods do not necessarily have a triggering event and are more long-lasting, pervasive states than emotions (e.g., Gross, 2008). Despite their theoretical distinction, the concepts of affect, mood and emotion are often used interchangeably (e.g., Laborde et al., 2013; Tamminen & Bennett, 2017), also in the depicted theoretical approaches that we will present. However, the main focus of the present study is affect and emotions as we intend to generate temporary specific situations to which affective and emotional changes can be attributed.

With regard to physiological reactions that are also formed based on the stress and emotional response to stressful situations (Lazarus, 2000), hormonal correlates and parasympathetic nervous system’s activity responses have been shown to provide objective data (e.g., Casto & Edwards, 2016). Particularly, salivary cortisol measures have been established as a reliable, noninvasive method applicable in sport psychological research (e.g., Coelho, Keller, & Da Silva, 2010). Adaptive increases of cortisol have been shown as anticipatory stress response prior to competitive situations as well as during competition (Lautenbach, Laborde, Klämpfl, & Achtzehn, 2015). While heart rate (HR) is a parameter often monitored in connection with the intensity of exercise, individual heart rate variability (HRV), and specifically its vagally-mediated components (so-called vagally-mediated HRV, vmHRV) is mostly considered to investigate how the body reacts to stress and recovery (see review by Mosley & Laborde, 2022). In competitive scenarios, heightened activation and cardiovascular levels have been demonstrated to signify higher stress levels compared to non-competitive contexts (e.g., García-León, Reyes Del Paso, Robles, & Vila, 2003). According to the vagal tank theory (Laborde, Mosley, & Mertgen, 2018), higher vmHRV values indicate better adaptability to environmental challenges, including physical, affective, or cognitive demands. Within the theoretical framework, the image of a tank is used, which is filled or emptied depending on the situation. The filling status of the tank is applied to three different levels (Resting, Reactivity and Recovery). Likewise, on the hormonal level, the interaction of psychological and physiological stress responses before, during and after a competition are depicted in the model of neuroendocrine and mood responses to a competitive situation (Salvador & Costa, 2009). Focusing on the competition phase of the model, active coping occurs among individuals who appraise a situation as challenging. This is accompanied by increases in testosterone and a decrease of cortisol as well as an activation of the sympathetic nervous system followed by positive mood changes. In contrast, situations appraised as threatening are suggested to provoke passive coping patterns related to a low activation of the sympathetic nervous system and release of testosterone accompanied by negative mood changes and increases in cortisol (Salvador & Costa, 2009).

2. Executive functions and sport performance

Based on the classification of the core executive functions (EFs) as top-down processes that contribute to the regulation of thoughts and behavior (Diamond, 2013; Miyake & Friedman, 2012), inhibition, cognitive flexibility, and working memory have been linked to athletic performance (see meta-analyses by Heilmann, Weinberg, & Wollny, 2022; Kalén et al., 2021). The relevance of EFs in soccer, in particular, stems from tactical advancements and evolved physical performance levels, promoting higher speed of play (Wallace & Norton, 2014). As a result, cognitive demands are increasingly coming into focus, especially the effective processing of situational information from a dynamically changing environment for fast and accurate decision-making (Albaladejo-García, García-Aguilar, & Moreno, 2023). Relatedly, study results suggest associations between soccer performance and tactical decision-making behavior, particularly for inhibition (Sakamoto, Takeuchi, Ihara, Ligao, & Suzukawa, 2018; Verburgh, Scherder, Van Lange, & Oosterlaan, 2014) and cognitive flexibility (Huijgen et al., 2015; Scharfen & Memmert, 2021; Vestberg et al., 2020).[1]

[1] The third core EF of working memory has been neglected in this study as the validation of a specific task was not yet completed at the time of data collection.

Inhibition comprises the “ability to deliberately inhibit dominant, automatic, or prepotent responses” (Miyake et al., 2000, p. 57) as well as irrelevant interfering distractors crucial for selective and sustained attention (Diamond, 2006). Cognitive flexibility or shifting refers to adapting attention and actions to shifting tasks or operations and corresponding demands (Miyake et al., 2000). Studies reporting the superiority of open-skill athletes over closed-skill athletes in inhibition and cognitive flexibility indicate their importance in game sports, as well as similar individual expressions of both functions (meta-analysis by Heilmann, Weinberg, & Wollny, 2022).

3. Theoretical models on stress and emotions on EFs

Stress and emotions have been known to impact sports performance (e.g., Frame & Reichin, 2019). Thereby, one pathway of influence can be via EFs (e.g., Lautenbach & Laborde, 2016). In this context, it is mandatory to differentiate between the investigated outcome (e.g., general or domain-specific cognitive performance), the complexity of performance (e.g., cognitive task and required functions) as well as the type of stressors and intensity that athletes were exposed to (Hepler & Andre, 2020; Lautenbach, 2017). Thus, empirical findings on relationships are hardly generalizable, as individual (e.g., sex, age, personality) and contextual factors (e.g., perception of the environment, task difficulty and utility) have to be taken into account (Grahek, Musslick, & Shenhav, 2020; Hamilton, Carré, Mehta, Olmstead, & Whitaker, 2015).

The attentional control theory is based on the assumption that emotions –especially anxiety– affect selective attention negatively by reducing cognitive control and, consequently, EF performance (Eysenck, Derakshan, Santos, & Calvo, 2007). In detail, anxiety leads to increased attention to salient stimuli, and thereby, a reduction of attention to task-relevant information. In this context, especially the efficiency of inhibition and shifting are affected by the enhanced distractibility due to anxiety (Eysenck & Derakshan, 2011). Empirical studies including athletes have shown that individual processing of emotional task-irrelevant information was negatively affected due to stress (e.g., Wilson, Wood, & Vine, 2009), however, there are studies that show the opposite effect, that is an increased focus on task-relevant information and faster decisions during stressful conditions (Hepler & Andre, 2020; Lautenbach et al., 2016).

Within the mood-as-information theory (Schwarz & Clore, 1983), affective states are presented as sources of information for the perception and processing of environmental stimuli. While negative moods are associated with a problem or a threat, positive moods are characteristically absent of potential dangers or concerns impacting modes of processing (Vaughan & McConville, 2021). Thus, the problematic environment causing negative mood promotes more careful and analytic cognitive processing (Mitchell & Phillips, 2007). Therefore, mood-as-information theory would predict negative mood to increase EF performance in comparison to neutral mood states (Mitchell & Phillips, 2007).

4. Empirical evidence about stress and EF performance

Empirical studies focusing on the impact of stress and emotions such as anxiety on EFs yield mixed results. Although stress has been associated with decreased functioning of the executive control network in the prefrontal cortex (Hermans, Henckens, Joëls, & Fernández, 2014), generalizability and predictability for EF performance are limited due to differences in individual stress responses and controllability of stress exposure (e.g., Henderson, Snyder, Gupta, & Banich, 2012). Controllability refers to the perception of control over stressors in terms of being able to influence outcomes through adaptive behavior, affecting the subjective stress response and physiological reactivity (Arnsten, 2009). In this context, an inverted U-shaped relationship has been suggested according to which moderate stress facilitates EF performance while low and high-stress levels lead to deterioration (Arnsten, 2009; Henderson et al., 2012). Correspondingly, positive and negative effects of stress have been reported. Improvements in task switching and Stroop paradigms (Kofman, Meiran, Greenberg, Balas, & Cohen, 2006; in athletes: Lautenbach et al., 2016), response inhibition (Schwabe, Höffken, Tegenthoff, & Wolf, 2013) as well as dual-tasking performance (Beste, Yildiz, Meissner, & Wolf, 2013), have been demonstrated under acute psychosocial stress. In contrast, also performance deteriorations were shown in task switching and cognitive flexibility (Alexander, Hillier, Smith, Tivarus, & Beversdorf, 2007; Plessow, Kiesel, & Kirschbaum, 2012). In addition, greater impairment of EFs has been associated with higher cortisol release, pointing to the influence of neuronal correlates (Schoofs, Wolf, & Smeets, 2009). However, the effects of stress and its influence on EFs cannot be attributed merely to differences in cortisol levels, as the broader impact of general stress has been shown to produce different effects on EFs compared to isolated cortisol administration (see Lautenbach, 2017; meta-analysis by Shields, Sazma, & Yonelinas, 2016). Overall, it has been shown that higher stress levels are associated with decreased EFs (see review by D’Amico, Amestoy, & Fiocco, 2020).

With regards to stress-related emotions, empirical findings demonstrate similar divergent findings. In accordance to the attentional control theory (Eysenck et al., 2007), it has been shown that anxiety and frustration contribute to higher intraindividual variability (Pnevmatikos & Trikkaliotis, 2013), that is the variability of repeated measurements within an individual and here refers to short-term fluctuations in a person’s EF performance over the course of a task. In contrast, Shields, Moons, Tewell, & Yonelinas, 2016 could not show EF impairment for the likewise negative affective state of anger. Thereupon, the authors emphasized a differentiation of emotional states with negative valence and high-arousal because of non-generalizable effects on EFs. Against this background, little empirical support exists for generalizing predictions proposed in the framework of cognitive load theory and mood-as-information theory. Nevertheless, fluctuations in emotional states can produce different effects on EFs and are thus, relevant to investigate (Mitchell & Phillips, 2007).

5. The present study

A relevant question regarding the assessment of EFs refers to their variability in different contexts and situations. Accordingly, it has been questioned whether single EF measures and scores are sufficient to draw conclusions about individual levels of performance as well as their contribution to sport performance or expertise (Furley, Schütz, & Wood, 2023; Pnevmatikos & Trikkaliotis, 2013). Therefore, the diagnosis of EFs considering game-related stress factors could provide valuable insights into EF performance alterations in youth elite athletes. In addition, investigations of EFs under sport-specific stressors are scares but needed because they potentially allow for a more direct translation to the soccer field (Lautenbach et al., 2016). Hence, this study aims at generating a game-related stress condition eliciting psychophysiological stress responses to examine the effects on EF performance compared to a neutral condition. Through the assessment of psychological and physiological parameters reflecting emotional states, as well as hormonal and cardiovascular situational adaptations, we account for limitations of previous studies and could possibly help explain variances in EF performance that have previously been reported (e.g., Beavan et al., 2020).

We expect our psychophysiological stress induction to lead to an increase in psychophysiological stress (i.e., increase in perceived stress, anxiety, cortisol, heart rate; decrease in positive emotions, and vmHRV) based on previous research (e.g., Hayes, Grace, Baker, & Sculthorpe, 2015; Lautenbach et al., 2016; van Paridon, Timmis, Nevison, & Bristow, 2017; hypothesis 1). Furthermore, we hypothesize that EF performance is significantly affected by the stress condition (hypothesis 2a), due to the manifold aspects presented (i.e., appraisal, personal and contextual factors). We do not specify the direction of effects due to inconsistent empirical findings and theoretical predictions. Finally, we expect an increased variance in EF performance in the stress condition compared to the neutral condition (e.g., McKinney, Euler, & Butner, 2020; Knöbel, Weinberg, Heilmann, & Lautenbach, 2024; hypothesis 2b).

6. Method

6.1. Participants

A total of 92 male[2] soccer players from the youth academy of a German first-division soccer club participated in the study (M_{age} = 15.17, SD_{age} = 1.45). They belonged to U15, U16, U17, and U19 youth teams. On average, participants had played soccer for 10.1 years (*SD* = 2.48) and reported an average weekly training volume of 10.86 h (*SD* = 2.55). At the time of data collection, from June to October 2021, all teams played at the highest national level of their respective age group. Participants were not diagnosed with behavioral, learning, or medical conditions that might influence cognitive abilities. Prior to the investigation, participants or their legal guardians (for players under 18) signed written informed consent collected by the club. The study was carried out in accordance with the Declaration of Helsinki and approved by the ethics committee of Leipzig University (2020.11.17_eb_69).

6.2. Measures

6.2.1. Subjective measures of psychophysiological stress

6.2.1.1. Stress, affective states and emotions. ***Perceived Stress.*** Perceived stress was measured on a visual analog scale (VAS; Crichton, 2001). Players were presented with a 100-mm line to answer the question “How stressed do you feel right now?” from 0 ("not at all") to 100 ("extremely").

Affective States. Valence and arousal of participants were recorded using Self-Assessment Manikins (SAM; Bradley & Lang, 1994). The SAM is a non-verbal assessment using pictorial representations of facial expressions to assess affective reactions regarding valence and arousal. It consists of one row of five pictograms representing the two affective dimensions. Participants were asked to answer how they feel right now on a 9-point scale from 1 (“unpleasant”) to 9 (“pleasant”) for valence, and from “calm” (1) up to “excited” (9) for arousal. Objectivity and reliability of the SAM has been established (Morris, 1995).

Competitive Anxiety. Based on the outlined conceptual overlaps between stress and anxiety, we assessed state competitive anxiety. For this purpose, we used the German version (Ehrlenspiel, Brand, & Graf, 2009) of the Competitive State Anxiety Inventory-2 (CSAI-2; Martens, Burton, Vealey, Bump, & Smith, 1990). The questionnaire distinguishes three components of competitive anxiety, each of which is formed from four items with answer options ranging from 1 (“not at all”) to 4 (“extremely”). The somatic anxiety component involves the perception and experience of physical signs of anxiety (i.e., heart beating, clammy hands or queasy stomach; α = 0.69). Cognitive anxiety depicts the perception of worry and negative expectations (α = 0.74). Additionally, a third component (self)-confidence encompasses the perception of good preparation and optimism regarding an upcoming competition, which potentially provides information about the appraisal as a challenge rather than a threat (Ehrlenspiel et al., 2009).

6.2.1.2. Objective measures of psychophysiological stress. ***Cortisol.*** Samples of saliva were collected throughout the experimental procedure to assess cortisol and, thereby, objectively control for stress (Coelho et al., 2010). Prior to the experiment, players were instructed not to eat or drink anything but water and not to brush their teeth 1 h before the start of testing to reduce the risk of sample contamination. In total, six samples were collected from each participant at previously defined measurement times (i.e., t_1 = baseline, t_2 = after warm-up, t_3 = after cognitive task pre-test, t_4 = after stress vs. neutral induction, t_5 = after cognitive task post-test, t_6 = after cooldown). All samples were collected via plastic saliva collection tubes. Participants were asked to spit into the tube using plastic straws. Complete samples were stored in a refrigerator at −20 °C on the same day. Salivary cortisol levels (nmol/l) were determined by using commercial enzyme-linked immunosorbent assay (ELISA) kits (Salivary Cortisol ELISA, SLV-2930, DRG Instruments GmbH, Germany).

Heart Rate and Heart Rate Variability. HR and HRV were measured with an ECG device (i.e., Bittium Faros 180°, IP67, Kuopia, Finland) attached to two disposable ECGs (Ambu L-00-S/25, Ambu GmbH, Bad Nauheim, Germany). One electrode was placed in the right infraclavicular fossa, and one was placed on the left side of the chest (e.g., Laborde et al., 2021). Players wore the device during the entire experimental procedure. The start and end times of the tasks performed were documented and then divided into 3-min sequences (adapted following recommendations of Laborde, Mosley, & Thayer, 2017) around the measurement times of cortisol. The division into 3-min sections resulted in six measurement time points for each player (i.e., t_1 = baseline, t_2 = warm-up, t_3 = pre SB task, t_4 = physical exercise, t_5 = post SB task, t_6 = outline). HR was analyzed to track and compare the intensity of the exercises. For vmHRV, the root square of successive differences (RMSSD) was extracted to investigate cardiac vagal activity (Laborde et al., 2017). HR and vmHRV data were analyzed with Kubios HRV software. Kubios' medium correction algorithm was used to identify and exclude sections with more than 5 % artefacts. The medium threshold correction method was chosen based on the default settings of Kubios software and previous comparative studies on artifact correction. Thus, higher settings were avoided due to the risk of excessive data interpolation, potentially compromising the accuracy of the analysis (e.g., Alcantara et al., 2020; Rogers, Giles, Draper, Mourot, & Gronwald, 2021). Afterward, the ECG signal was visually inspected for each section and artifact correction was performed manually (Laborde et al., 2017).

6.2.2. Executive functions

Inhibition and cognitive flexibility were assessed in a soccer-specific setting[3] (i.e., SoccerBot360; (Musculus et al., 2022). The SoccerBot360 (SB) is a circular training device with a diameter of 10 m that provides for a 90-m^2 field surrounded by a 32-segment wall, each segment 1 m wide and 2.5 m high, serving as a projection area for the training content and against which played balls can be kicked. An integrated high-speed camera enables the capture of essential metrics including response time, processing speed, and accuracy. For response times, the SB initiates timing when the ball leaves the foot of the player. Accordingly, the players are instructed to play from a marked point in the centre of the SB. However, slight deviations may occur due to movements when passing and receiving the ball. The foot with which the ball is played can be freely chosen and permanently changed by the players (e.g., right and left foot alternately).

Inhibition. Players performed a soccer-specific flanker task to measure inhibition, where five soccer players were presented from the side (Figure 1A). In accordance with the computerized flanker task (Eriksen & Eriksen, 1974), the target was the middle player, with two distracting players on each side. Depending on the direction the target player faced, participants were asked to kick the ball into the left or right goal presented on either side of the players. In congruent trials all players faced the same direction. In contrast, for incongruent trials, the target and the

[2] Baseline data of emotional states and EF performance from this sample have been previously reported (see Knöbel et al., 2024). Analysis on psychophysiological stress responses and their impact on EF performance are exclusively reported in the current manuscript.

[3] Soccer-specific refers to the testing modalities, in which participants were standing and responded to stimuli specifically by passing into goals.

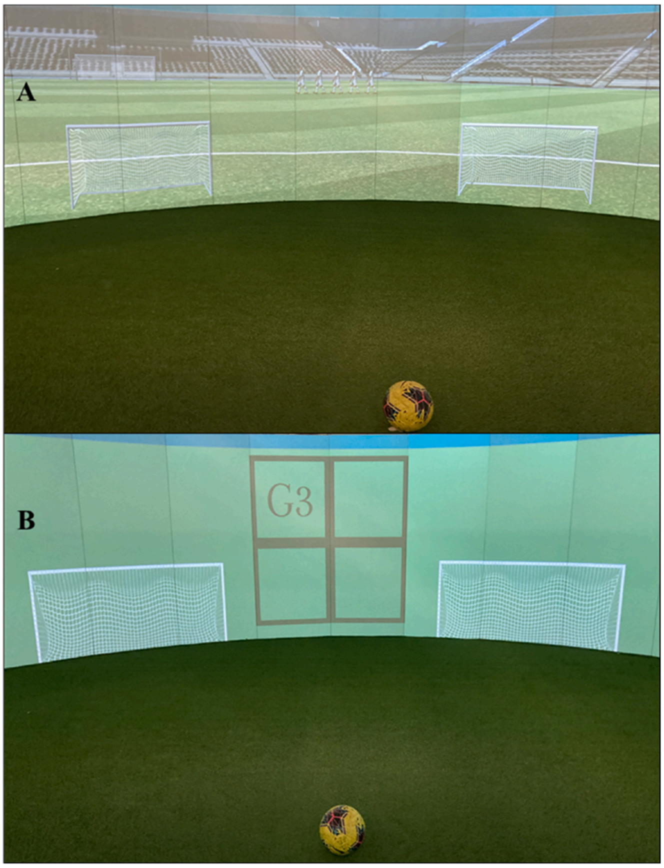

Fig. 1. Tasks for inhibition (A) and cognitive flexibility (B) in SoccerBot360.

flanker players were aligned in opposite directions. The task consisted of four practice trials, followed by 54 test trials (36 congruent, 18 incongruent, see (Musculus et al., 2022)).

Response times for correct responses in ms and accuracy in % were collected for congruent and incongruent trials. Additionally, the flanker effect was calculated by subtracting the mean response times of congruent trials from incongruent trials. Furthermore, to investigate intraindividual performance variability, we determined the standard deviation of the individual response times for congruent and incongruent trials. The reliability of the task can be considered excellent (congruent trials: $\alpha = 0.97$; incongruent trials: $\alpha = 0.96$).

Cognitive Flexibility. Cognitive flexibility was assessed using a version of the number-letter task (Rogers & Monsell, 1995) adapted by Miyake et al. (2000). It contains a 2 × 2 matrix that displays sequentially clockwise a pair of characters in one of four boxes (see Figure 1B). Thereby, the combination of either even (2, 4, 6, 8) or odd (3, 5, 7, 9) numbers and either vowel (A, E, I, O) or consonants (G, K, M, R) has to be assessed regarding the position in the matrix. Only the letter is relevant in the upper boxes, whereas the number functions as a distractor and vice versa in the lower boxes. Participants had to pass into the left goal for consonants and even numbers and the right goal for vowels and odd numbers. The task was introduced by a total of 24 practice trials in three blocks (8 non-switch runs for letters, 8 non-switch runs for numbers; 8 combined trials). In non-switch trials, the stimuli remain in the lower or upper row. In switch trials, participants have to switch between focusing from letters to numbers or vice versa. Practice trials were followed by 56 test trials in two blocks (14 no-switch, 14 switch trials in each block following the clockwise sequence).

Response time in ms and accuracy scores of correct responses in % for the switch and no-switch trials were assessed. The difference between the no-switch and switch trials for response time and accuracy reflects the switch costs. Lower switch costs are associated with higher cognitive flexibility. Also, intraindividual variability was determined for the switch and no-switch trials analogous to the proceeding for the flanker task. The reliability of the task can be considered excellent (switch trials: $\alpha = 0.92$; no-switch trials: $\alpha = 0.94$).

6.3. Induction of psychophysiological stress

The stress induction aimed to represent the demands of a competitive soccer game as accurately as possible, immediately before and during the cognitive task. Thus, we combined psychological and physiological stressors during the experiment to simulate a game-related psychophysiological stress condition.

6.3.1. Psychological stress: evaluative instructions of a competitive situation

To ensure that the players would call up the high intensity during the soccer-specific load (i.e., Hoff test, see below), they were informed in advance that the number of runs would be documented and ranked afterward so that players' performances could be compared. The instructions were intended to create a competitive situation through which psychophysiological reactions should be provoked (e.g., Salvador & Costa, 2009). The same instruction was given for performing the cognitive task in the SoccerBot360 to ensure that participants tried to retrieve their best possible performance. We used additional factors to induce psychosocial stress, which we selected based on recommendations of Baumeister and Showers (1986) and evidence from sports that support the effectiveness (Jackson, Ashford, & Norsworthy, 2006; Lautenbach et al., 2016). Besides the instruction concerning a competitive situation, players in the stress condition were informed that camera footage would be taken of the following tasks to analyze and evaluate them afterward. Subsequently, the complete run of the Hoff test was recorded with a tripod camera. During the cognitive task that followed, a webcam was installed and placed so that the player had live footage of his performance on a computer screen in his peripheral vision. This setup should increase the players' self-awareness and was reinforced by a second experimenter (Lautenbach et al., 2016). The second experimenter was introduced to observe and document the behavior, movements, and body language during the task, which was also communicated to the players. Thus, the second experimenter observed the players in the SB and took handwritten notes to give the players the impression of permanent observation and evaluation (Lautenbach et al., 2016).

6.3.2. Physiological stress: Hoff test

To induce physical stress, players completed the Hoff test (Hoff, Kähler, & Helgerud, 2006). The Hoff test consists of a course with various soccer-specific movement tasks (e.g., dribbling, passing, jumping, running forwards, and backward). The test was initially designed for the football-specific enhancement of maximum oxygen uptake (VO_2 max) during training. The originally specified dimensions for the test, which were 30 m wide and 35 m long, had to be adapted and reduced for the available field (see supplementary material section A). Players were instructed to run the complete course as many times as possible in 10 min. Through this instruction, the intermittent physical demands of a competitive match (Randers, Nielsen, Bangsbo, & Krustrup, 2014) should be replicated at an average intensity of 80–90 % of the maximum individual heart rate (Stølen et al., 2005).

6.4. Procedure

Players were informed about the study by their coaches and sports psychologists before data collection started during the teams' preseason preparation in June 2021. Written informed consent was obtained from the participants or their legal guardians before testing. The experiment was conducted in the sports hall of the youth soccer academy and lasted approximately 60 min for each player. All instructions were presented on a tablet screen showing videos recorded in advance to ensure standardized information for all participants. Subjective data on perceived stress and emotions were also assessed digitally on a tablet.

The study followed a pre-post cross-sectional approach using a between-subject design for the baseline followed by a within-subject design (neutral vs. stress condition). All players were randomly assigned to a condition (stress vs. neutral) in advance. The assigned tasks (flanker task: $n = 45$ vs. number-letter task: $n = 47$) were counterbalanced.

In the stress condition, the players were introduced to a competitive setting, including camera recordings for subsequent analysis and evaluation of the subsequent tasks. They were then familiarized with the demands and procedure of the standardized Hoff test, which was performed for a given time of 10 min.

The neutral group received no instruction of a competitive situation and performed 10 min of moderate soccer-specific exercise consisting of a stretching program followed by a technical task in which the ball had to be juggled between cones. The physical preparation and exercises (warm-up, Hoff test vs. moderate load) were completed on an artificial ground area next to the SB in order to keep the distances between the tasks short and, especially in the stress condition, to be able to prevent complete recovery after induced exertion. A detailed presentation of the experimental procedure is depicted in Figure 2 and a detailed verbal description can be found in the supplementary material (section A).

6.5. Data preparation

To prepare the data, various exclusion criteria and filter processes were applied before the statistical analyses. Subjects with missing data were excluded from analyses involving these data (i.e., two players with missing answers for stress, affect and anxiety; two players for single components of anxiety; one player for t_3 cortisol due to an insufficient amount of saliva). For cardiovascular parameters HR and RMSSD, data from players with artefacts that exceeded 5 % of the medium threshold for artifact correction in Kubios (i.e., six players) across all sections were removed from manipulation check. For the inhibitory task, three different filters were applied. A first filter excluded all incorrect responses (pre: 0.25 %, post: 0.42 %). In the second filter, trials with response times lower than 400 ms and higher than 3000 ms were removed (pre: 0.97 %, post: 0.38 %) to account for extreme results (Musculus et al., 2022). The third filter excluded response times higher or lower than three standard deviations from the individual mean (pre: 1.01 %, post: 1.09 %). One player had to be excluded from analyses of cognitive performance due to an overall error rate higher than 50 % (i.e., 74.07 %) identified by the third filter in post-test (stress condition). For cognitive flexibility, three participants were excluded due to an overall error rate higher than 50 % (postulated hit rate of guessing, e.g., Flowers, Bolton, & Brindle, 2008) in the pre-test. After exclusion, filters were applied analogously to the flanker task (1st filter: pre: 12.95 %, post: 6.17 %; 2nd filter: pre: 5.28 %, post: 2.31 %; 3rd filter: pre: 0.97 %, post: 1.38 %).

Due to the exclusion and filtering processes, not all analyses include the same number of subjects. However, since the sample size is limited due to specificity (i.e., youth elite players of one club), we aimed to include as many players as possible in the analyses.

6.6. Data analysis

A check of normal distribution was omitted based on the central limit theorem, which states that the sampling distribution will be approximately normally distributed for group sizes of $N \geq 30$ (Tavakoli, 2012). All data were analyzed using SPSS statistics, version 27, with a significance level set at $p = 0.05$ for all analyses. Outliers and missing data were identified and excluded only with respect to the specific construct (e.g., six players for t_1 cortisol due to increased baseline levels; see Van Goozen et al., 1998). Please see Supplement Material (section B) for a detailed description of detected outliers.

For the manipulation check (hypothesis 1), we conducted a 2 (time$_{within}$: pre vs. post stress induction) x 2 (condition$_{between}$: neutral vs. stress) repeated measures (rm) MANOVA including psychological parameters (i.e., competitive anxiety) that were assessed before and after the stress induction with time (pre vs. post-stress induction) as an independent within-subject factor and condition (neutral vs. stress) as between-subject factor. Further, to assess psychophysiological changes throughout the study procedure, we conducted two additional rmMANOVAs: The first 6 (time$_{within}$: t_1 vs. t_2 vs. t_3 vs. t_4 vs. t_5 vs. t_6) $\times$ 2 (condition$_{between}$: neutral, stress) MANOVA including psychological parameters (i.e., stress, valence and arousal) and the second 6 (time$_{within}$: t_1 vs. t_2 vs. t_3 vs. t_4 vs. t_5 vs. t_6) $\times$ 2 (condition$_{between}$: neutral vs. stress) rmMANOVA including physiological stress parameters (i.e., cortisol, HR, and RMSSD), both with time (t_1 vs. t_2 vs. t_3 vs. t_4 vs. t_5 vs. t_6) as an independent within-subject factor and condition (neutral vs. stress) as between-subject factor.

With regard to our main hypothesis (hypothesis 2a), the change in cognitive performance between the neutral and stress conditions was investigated with two separate 2 (time$_{within}$: pre vs. post) x 2 (condition$_{between}$: neutral vs. stress) rmMANOVAs: To assess changes in inhibition, response time (RT) for congruent trials, RT for incongruent trials, RT flanker effect, accuracy for congruent trials, accuracy for incongruent trials, and accuracy flanker effect in the first rmMANOVA. To assess changes in cognitive flexibility, RT for no-switch trials, RT for switch trials, RT switch costs, accuracy for no-switch trials, accuracy for switch trials, and accuracy switch costs were entered in the second rmMANOVA.

Finally, to examine whether variance in cognitive performance can be explained by psychophysiological stress (hypothesis 2b), the variance (standard deviation) of response times for every trial in the respective

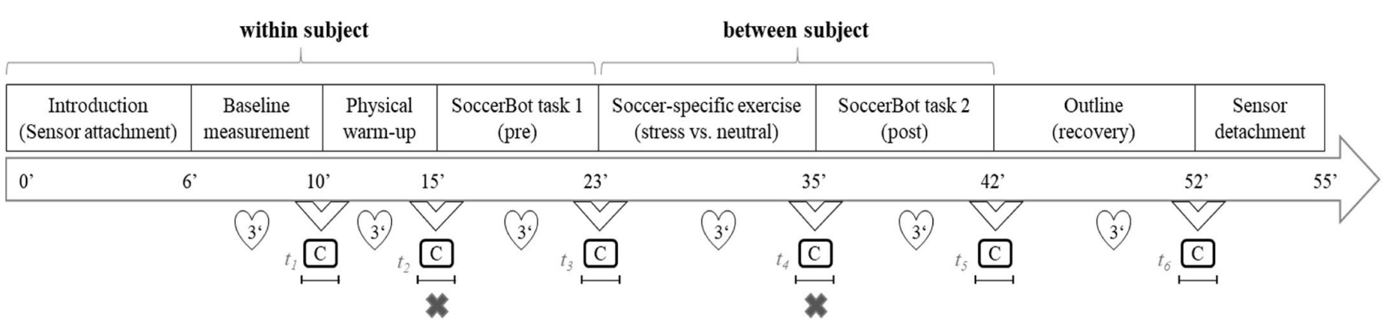

Fig. 2. Experimental timeline. Note. 3': Heart rate and heart rate variability (3 min); ⊢⊣: perceived stress, valence and arousal; C = Cortisol; ✖ = competitive anxiety.

conditions was considered in a separate analysis. Consequently, we conducted the same 2 ($time_{within}$: pre vs. post) × 2 ($condition_{between}$: neutral vs. stress) rmMANOVA with the variance (in ms) for no-switch trials and switch trials (number-letter task) and the variance for congruent and incongruent trials (flanker task) as dependent variables.

7. Results

7.1. Manipulation check: psychophysiological stress induction

After exclusion of missing or erroneous (e.g., HR and RMSSD) data, all analyses were conducted with and without statistical outliers. Similar patterns of results could be observed, so all analyses are reported with outliers. Descriptive statistics for all variables concerning the manipulation check can be seen in Table 1.

The rmMANOVA for the psychological parameters of competitive anxiety showed a significant main effect of time Wilks' λ = 0.029, $F(3, 84) = 946.95$, $p < 0.001$, $\eta p^2 = 0.97$ and a significant interaction effect between time and condition Wilks' λ = 0.828, $F(3, 84) = 5.83$, $p = 0.001$, $\eta p^2 = 0.17$. Univariate analysis with Greenhouse-Geisser correction showed a significant interaction effect between time and condition for somatic anxiety $F(1, 86) = 12.07$, $p < 0.001$, $\eta p^2 = 0.12$ and cognitive anxiety $F(1, 86) = 6.92$, $p = 0.010$, $\eta p^2 = 0.07$. Thus, both cognitive and somatic anxiety exhibited a significant increase in the stress condition from pre to post, whereas no significant changes were found in the neutral condition.

The rmMANOVA for the psychological parameters perceived stress, valence, and arousal revealed a significant main effect of time Wilks' λ = 0.330, $F(15, 74) = 10.01$, $p < 0.001$, $\eta p^2 = 0.67$ as well as significance for the interaction effect between time and condition Wilks' λ = 0.485, $F(15, 74) = 5.23$, $p < 0.001$, $\eta p^2 = 0.51$. The follow-up univariate analysis (Greenhouse-Geisser) confirmed the significant interaction effect for perceived stress $F(3.34, 294.55) = 3.94$, $p = 0.007$, $\eta p^2 = 0.04$, valence $F(3.26, 287.62) = 13.03$, $p < 0.001$, $\eta p^2 = 0.13$ and arousal $F(4{,}01, 352{,}93) = 5.91$, $p < 0.001$, $\eta p^2 = 0.06$. In other words, perceived stress and arousal increased, while valence significantly decreased within the stress condition, in contrast to the neutral condition where such changes were not observed. Mean values of psychological parameters are depicted in supplementary material (Figure C1).

For the physiological markers of stress, namely cortisol, HR and RMSSD, the rmMANOVA showed a significant main effect of time, Wilks' λ = 0.041, $F(15, 63) = 97.04$, $p < 0.001$, $\eta p^2 = 0.96$ and a significant interaction effect between time and condition, Wilks' λ = 0.203, $F(15, 63) = 4.44$, $p < 0.001$, $\eta p^2 = 0.79$. Additional controlling for the time of the day by entering it as a covariate did not change the results, $F(15, 62) = 1.25$, $p = 0.261$, $\eta p^2 = 0.23$; meaning that the time of the day did not affect the physiological stress response. Follow-up univariate analysis with Greenhouse-Geisser correction showed a significant condition and time interaction effect for HR, $F(3.92, 302.42) = 53.43$, $p < 0.001$, $\eta p^2 = 0.41$, RMSSD, $F(3.38, 260.47) = 7.67$, $p < 0.001$, $\eta p^2 = 0.09$ and Cortisol, $F(2.82, 217.32) = 7.84$, $p < 0.001$, $\eta p^2 = 0.09$. In summary, cortisol concentration, mean heart rate, and RMSSD exhibited significant changes in the stress condition, whereas they either remained steady or displayed minor adaptations in the neutral condition. Changes of saliva cortisol concentration during the experimental procedure presenting mean values for both conditions as well as cardiovascular parameters with respect to measurement time and condition are presented in supplementary material (section C).

Overall, all analyses of psychological and physiological parameters indicate the effectiveness of the stress induction, providing the basis for further analysis investigating associated differences in cognitive performance (hypothesis 1).

7.2. Stress and cognitive performance

All descriptive statistics with regard to cognitive performance are presented in supplementary material (section C). For inhibitory performance (hypothesis 2a), statistical analyses revealed a significant main effect of time Wilks' λ = 0.615, $F(4, 39) = 6.10$, $p < 0.001$, $\eta p^2 = 0.38$ but no significant interaction effect between time and condition Wilks' λ = 0.902, $F(4, 39) = 1.06$, $p = 0.388$, $\eta p^2 = 0.09$ in the rmMANOVA. No significant interaction effects were found at the univariate level either. To scrutinize the results, we conducted independent *t*-tests and dependent *t*-tests for the flanker effect as the task critical parameter for inhibition. Participants in the stress condition showed significantly better inhibitory control after the stress induction in comparison to the control condition, $t(42) = 2.90$, $p = 0.006$, $d = 0.88$. For participants in the stress condition, however, no significant change in inhibitory control was detected from pre to post, $t(18) = 1.55$, $p = 0.130$, $d = 0.35$.

Regarding cognitive flexibility performance (hypothesis 2a), we found a significant main effect of time Wilks' λ = 0.465, $F(4, 42) = 12.09$, $p < 0.001$, $\eta p^2 = 0.54$, indicating improvements in both groups from pre to post-test. We detected no significant time × condition interaction Wilks' λ = 0.896, $F(4, 42) = 0.84$, $p = 0.506$, $\eta p^2 = 0.07$. Also, no significant univariate interaction effects could be determined. Subsequent *t*-tests for switch costs showed that the difference between both conditions in post-task was not significant $t(42) = 1.38$, $p = 0.188$, $d = 0.40$ and neither was the difference between pre and post-task within the stress group $t(23) = 1.70$, $p = 0.103$, $d = 0.34$. Figure 3 contains the graphical representation of switch costs and flanker effect for both measurement times in relation to the condition.

As a novel analysis, alterations of variance in cognitive performance

Table 1
Descriptive statistics on physiological and psychological parameters collected to examine effectiveness of stress induction.

Variable	Baseline (t_1)				After stress induction (t_4)							
					Stress				Neutral			
Physiological parameters *(6x)*	*M*	*SD*	*Max*	*Min*	*M*	*SD*	*Max*	*Min*	*M*	*SD*	*Max*	*Min*
HR (in bpm)	88.30	13.37	132.94	61.53	175.49	14.65	199.76	120.91	131.82	21.88	190.98	89.60
HRV (in RMSSD)	25.81	12.73	74.35	2.73	14.62	13.63	60.72	1.92	12.78	13.22	75.31	2.49
Cortisol (in nmol/l)	13.73	7.21	39.19	3.78	15.38	7.91	34.33	3.62	12.61	8.42	43.28	3.97
Psychological parameters *(6x)*												
Perceived stress	13.30	16.29	73	0	44.26	22.44	84	0	28.15	22.88	84	0
Arousal	2.94	1.78	9	1	4.28	2.05	9	1	3.23	1.92	9	1
Valence	7.63	1.20	9	4	5.23	1.9	9	1	7	1.43	9	2
Psychological parameters *(2x)*	**Pre**				**Post**							
					Stress				Neutral			
Somatic anxiety	5.43	1.30	9	4	6.88	1.72	11	4	5.30	1.54	11	4
Cognitive anxiety	5.68	1.49	10	4	5.69	1.82	11	4	5.28	1.57	9	2
(Self)-confidence	12.83	1.92	16	8	12.24	2.41	16	7	13.28	2.02	16	9

Note. 6x = variables that were collected six times throughout experimental procedure (t_1 = baseline, t_2 = warm-up, t_3 = pre SB task, t_4 = physical exercise, t_5 = post SB task, t_6 = outline), 2x = subjective variables that were collected two times (pre vs. post).

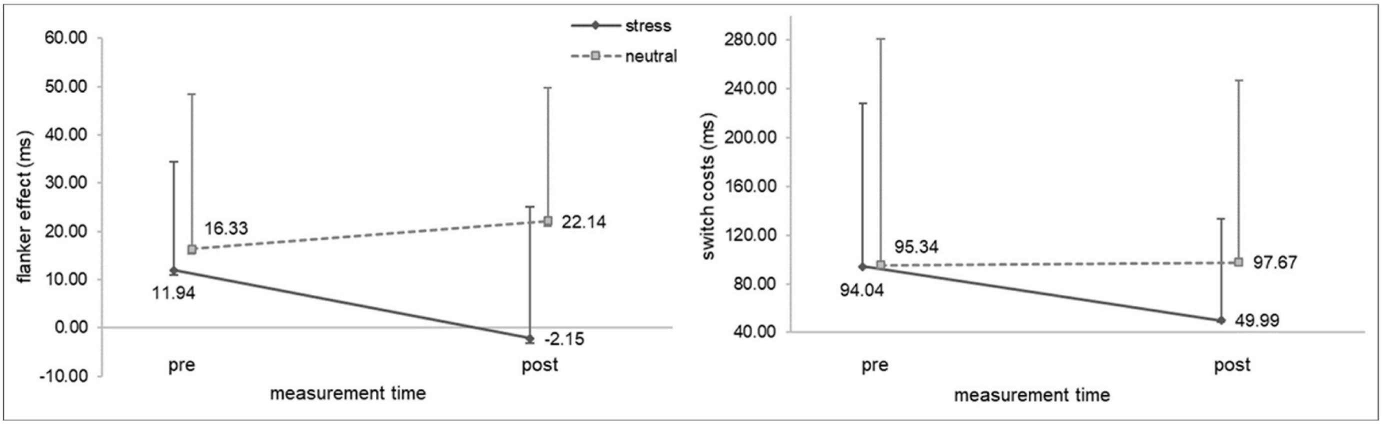

Fig. 3. Switch costs and flanker effect (in ms) for pretest and posttest for neutral and stress condition.

were investigated for both tasks (hypothesis 2b). For congruent and incongruent trials in the flanker task, no significant main effect of time Wilks' $\lambda = 0.922$, $F(2, 41) = 1.72$, $p = 0.191$, $\eta p^2 = 0.07$ but a significant interaction effect of time and condition was present Wilks' $\lambda = 0.730$, $F(2, 41) = 7.59$, $p < 0.005$, $\eta p^2 = 0.27$. Univariate analysis with Greenhouse-Geisser correction revealed a significant interaction for time × condition for the variance in congruent $F(1, 42) = 14.08$, $p < 0.001$, $\eta p^2 = 0.25$ and the variance in incongruent trials $F(1, 42) = 11.89$, $p = 0.001$, $\eta p^2 = 0.22$ indicating that variance in inhibitory performance is lowered during stress. Both progressions are shown in Figure 4.

With regard to cognitive flexibility, rmMANOVA for standard deviations within no-switch and switch trials showed a significant main effect of time Wilks' $\lambda = 0.670$, $F(2, 41) = 10.10$, $p < 0.001$, $\eta p^2 = 0.33$. However, a significant interaction effect could not be detected Wilks' $\lambda = 0.918$, $F(2, 41) = 1.83$, $p = 0.173$, $\eta p^2 = 0.08$.

8. Discussion

This study aimed to understand the impact of soccer-specific psychophysiological stress on EFs (i.e., inhibition, cognitive flexibility). Therefore, a game-related stress condition with demands of a competitive match was designed and implemented in a laboratory setting to control for potential confounders. Results show that the stress induction was successful and led to a significant increase in psychophysiological stress responses. Within statistical analyses, we did not detect significant changes in EF performance across all participants due to increased stress. Several factors may have contributed to the non-significant findings on EF performance so that the results must be interpreted against the background of different theoretical constructs and explanatory approaches. However, upon closer examination of the descriptive statistics, there were indications suggesting potential improvements in EF performance within the stress condition. In addition, a statistically significant lower variance of response times in inhibitory performance also indicates a potentially positive influence of stress.

8.1. Successful stress induction

Psychophysical stress was induced successfully by generating a competitive situation under the integration of game-related psychological and physiological stressors. This is in line with the theoretical assumptions according to the model of neuroendocrine and mood responses to a competitive situation (Salvador & Costa, 2009), suggesting an increase of psychophysiological stress responses in the context of competition as well as previous empirical findings (e.g., Coelho et al., 2010; Hayes et al., 2015; Lautenbach et al., 2016). Even though the constraints of a laboratory stressor were present, physiological parameters indicate that players reached an average intensification of 80–90 % of the maximum individual heart rate, characteristic for a competitive game (Stølen et al., 2005) as well as comparable in-game cortisol levels (Filaire, Bernain, Sagnol, & Lac, 2001) in the stress condition. In addition, the results are consistent with the vagal tank theory, which predicts a decrease in cardiac vagal activity due to a stress-induced increase in metabolic demands, as shown by vmHRV reactivity.

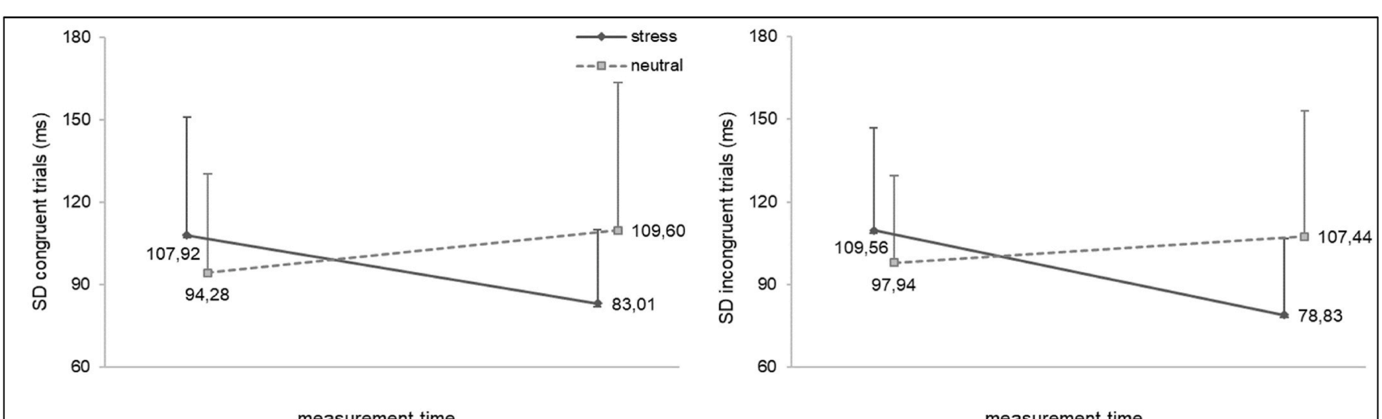

Fig. 4. Variance (SD) in response times between trials in congruent and incongruent condition of the flanker task for inhibition.

8.2. Effect of stress on EF performance

Contrary to our main hypothesis (2a), we did not find a significant effect of stress on EF performance in terms of response times and accuracy across participants in the conducted tasks for inhibition and cognitive flexibility. These findings contradict the general predictions of related theoretical models. Neither the reduced cognitive control and increased attention to task-irrelevant information associated with anxiety in the framework of attentional control theory (Eysenck et al., 2007) nor the more analytic processing and concentration for the task at hand caused by negative affect according to the mood-as-information theory (Schwarz & Clore, 1983) could be demonstrated across players.

On the one hand, we could argue that anxiety levels were high enough to impact attentional processes but that the interpretation of anxiety symptoms is rather facilitative for performance in our particular sample. In detail, based on the model of debilitative and facilitative competitive anxiety (Jones, 1995), the interpretation of anxiety symptoms determines the influence on performance. While threat-related stimuli are inevitably linked to negative expectations within attentional control theory, positive expectations can also persist in the individual's appraisal of the situation despite the presence of anxiety symptoms (Jones, 1995). Our results may suggest that the queried anxiety symptoms were equally present but were interpreted differently and thus, had different effects on performance. In this context, the peculiarity of our sample could be relevant. It has been argued that dealing with negative emotions is an important performance prerequisite in sports that athletes are confronted with from an early stage and are trained to do. Thus, regulating such emotions is less demanding on the prefrontal cortex and attentional capacities, reducing the impact on EFs (Vaughan & McConville, 2021, p. 685). However, without data on individual player perceptions or a comparison group from the general population, these interpretations remain speculative but suggest promising directions for future research.

On the other hand, although cognitive and somatic competitive anxiety were significantly increased in the stress condition, the anxiety levels reached were possibly not high enough, since the test situation is still different from a real competitive game (see also Lautenbach et al., 2016). Similarly, considering the decreased valence in the stress condition, the mean values of negative affect must also be interpreted as fairly low compared to other studies investigating anxiety or stress inductions or assessed emotional states in competitive situations (e.g., McCarthy, Allen, & Jones, 2013).

Another explanation for our results could be based on U-shaped functions that have been hypothesized to mediate the relationship between mood and cognitive performance (Mitchell & Phillips, 2007, p. 627). While for some players, induced stress possibly led to a moderate level of activation or alertness that promoted their performance (Arnsten, 2009; Hepler & Andre, 2022), other players were overwhelmed by the stress they were exposed to and needed more effort to exert control over distracting thoughts (Grahek et al., 2020), thereby showing a decrease in EF performance. Follow-up of individual results revealed that in the number-letter task, 14 players showed lower switch costs in the stress condition. This improvement compares with ten players with increased switch costs. The flanker task is even more balanced, with ten players showing a flanker effect reduction from pre to post and nine players where the flanker effect increased. Hence, the individual experience and expression of stress may serve as the most important explanatory approach, applicable to a range of personality-related factors. The theory of constructed emotions highlights the role of individual differences and the context in shaping emotional experiences. Varied experiences and reactions to stress may elicit differing intensities of psychophysiological responses and emotions (Barrett, 2017a; 2017b). Therefore, innate or learnt personality traits also play a substantial role. In competitive situations, different characteristics of the achievement motive can represent dispositions for the experience of stress. Specifically, fear of failure has been linked to the experience of stress and negative emotions as well as adverse performance outcomes in athletes within the same age range as our sample (Gustafsson, Sagar, & Stenling, 2017; Sagar, Busch, & Jowett, 2010). Conversely, hope for success has been shown to correlate with high task orientation, facilitating coping with stress and task performance in evaluative situations (Roedel, Schraw, & Plake, 1994; Tomczak, Kleka Paweł and Tomczak-Łukaszewska, & Walczak, 2024). Accordingly, players' personality structure and internalized concepts influence how they assess and manage the situation, determine which emotions arise from the confrontation and how these emotions affect their performance. Considering the age of our sample, during which personality traits are still developing and individual differences are apparent in past experiences and cultural influences, it seems likely that responses to stress, as well as potential performance consequences, are not consistent.

Despite our null result, descriptive data hints at a trend towards a reduction in the flanker effect and switch costs. While the flanker effect for response times was increased in the neutral condition (pre: 16.33 ms, post: 22.14 ms), a decrease could be observed in the stress condition (pre: 11.94 ms, post: −2.15 ms). We observed similar patterns for cognitive flexibility. In the neutral group, the switch costs slightly increased from pre- (95.34 ms) to post-test (97.67 ms), while they were considerably reduced in the stress condition (pre: 94.04 ms; post: 49.99 ms). These trends point to previous findings showing enhanced processing efficiency and decision making under stress (Beste et al., 2013; Hepler & Andre, 2020). It could be argued that the different stimuli are processed faster and more effectively under stress, reducing interference effects caused by task-irrelevant stimuli (Beste et al., 2013; Lautenbach et al., 2016). Future research may provide further insight into whether this trend applies specifically to athletes or is also present in the general population. In this context, other potential moderating variables could also be considered (e.g., age, sex or genetic differences; Heilmann, Wollny, & Lautenbach, 2022; Furley et al., 2023).

8.3. Variability of EF performance

Initially, even under neutral conditions in the pretest, the variability in response times between trials was considerably high. In other words, players needed a relatively long time to answer correctly in some trials and were very fast in others. This, in turn, is reflected in a large standard deviation of the flanker effect and switch costs and implies fluctuations in cognitive performance (e.g., Pnevmatikos & Trikkaliotis, 2013). The considerable variance in cognitive performance overall may provide an additional explanation for non-significant results. The greater the inconsistency in the player's performance during the pre-test and across the respective conditions throughout the task duration, the more difficult it is to identify significant differences based on mean values. Aligned with this perspective, Scharfen and Memmert (2021) suggested that the lack of significant effects could be attributed to potentially minor variations among players in a homogeneous sample of elite athletes. At this point, it would be insightful to examine changes at a more individual level. This could involve examining smaller groups, such as different teams and age categories, or players with similar psychophysiological stress responses, to determine if their performance undergoes significant changes.

In the stress condition, contrary to our hypothesis (2b), players showed less variability or, in other words, more constant inhibitory performance, whereas no significant differences in variability were present in the cognitive flexibility task. While the variability in the number-letter task was decreased for the players in both conditions in the post-test, a greater descriptive reduction was also shown in the stress condition (no-switch: pre: 288.61 ms; post: 205.83 ms; switch: pre: 318.62 ms; post: 228.10 ms) compared to the neutral condition (no-switch: pre: 340.34 ms; post: 308.67 ms; switch: pre: 320.86 ms; post: 281.73 ms). While the descriptive data has to be interpreted with caution, results of the flanker task indicate that the players' performance tended to become more stable under stress potentially due to a more careful cognitive processing (in accordance with mood-as-information theory). In contrast, the results are not in line with previous research reporting increased variability of cognitive performance in affective situations. However, those studies were conducted with children (Pnevmatikos & Trikkaliotis, 2013) or focused on different constructs (i.e., emotional reactivity, Gabel & McAuley, 2018). Studies focusing on athletes generally rather investigated the relationship of EFs and different (sport-specific) performance components at the group level (e.g., high and low-level athletes) than intra-subject variability in responses (Perri & Di Russo, 2017, p. 2). Yet, some neuroimaging studies investigated variability in EF performance with respect to the activity of large-scale brain networks. In a study with female varsity athletes, Roberts et al. (2022) found supportive evidence for findings from the general population, showing that low variability in reaction times is associated with higher activity of resting state networks (i.e., default mode; DMN). Based on further reports on stress-induced changes among brain networks and their activation (e.g., Zhang et al., 2019), the involvement of DMN could have contributed to the reduction of variability in our stress condition. Moreover, studies showed higher activation of the prefrontal cortex (PFC) associated with increased individual variability in response inhibition (e.g., Simmonds et al., 2007). The higher PFC activation was explained by potentially increased demands on individual top-down executive control. Thus, it could be that the increased activation of the DMN in the stress condition resulted in higher task engagement (e.g., Grahek et al., 2020) and that, as a consequence, players in the stress condition required less activation of the PFC to maintain executive control (Perri & Di Russo, 2017; Roberts et al., 2022). This however is speculative in nature and underlines the need for further research on intra-individual variability in athletes, as it could provide additional information on attentional capacities and allows a more accurate accurate assessment of EF performance (Roberts et al., 2022).

9. Limitations

Several limitations exist in the present study that should be considered when interpreting the results. First, all participants belonged to a youth academy of a professional soccer club and, thus, were characterized as elite youth athletes. Correspondingly, a certain experience in dealing with performance situations and thus, restricted generalizability of the data must be taken into account. A comparison with a control group of non-competitive or amateur-level players would have provided further insights to the role of expertise when understanding the impact of psychophysiological stress on EF performance (e.g., Vaughan & McConville, 2021).

Secondly, psychophysiological stress was induced in addition to the EF tasks and not as an integral part of the task (e.g., Shields, Moons, et al., 2016). Accordingly, we cannot say how the tasks contributed to the perceived stress or negative affect. On the one hand, it would have been informative to ask about the satisfaction with one's own performance and the perceived difficulty of the task. Without such data collected, differences in task expectancy and difficulty that potentially also affect cognitive performance (Grahek et al., 2020) remain speculative. On the other hand, the integration of visual and acoustic stressors (e.g., animation of spectators) could have increased stress induction during the task and rendered the test environment more representative of a real soccer match. Putting our findings into perspective, these considerations could represent methodological approaches for future research.

Thirdly, we performed statistical analyses excluding missing or erroneous data only from the analyses concerning the respective construct. This leads to a slightly varying number of cases between the analyses conducted. Nevertheless, the number of missing data within the different variables is relatively low and in all analyses the cases with complete data are over 90 % of the eligible cases (following Burton & Altman, 2004). Moreover, since the data are missing or erroneous randomly and the included subjects are not systematically different from the excluded subjects, we would argue that this does not bias our analyses (e.g., White & Carlin, 2010). In the context of missing data, HRV analyses should also be mentioned. Especially in study designs with excessive movements as in our stress condition, there is no possibility to correct specific movement artefacts. Using accelerometer data and our experimental protocol, we were able to identify sections in which the movement was extensive, but artefacts in these sections cannot be automatically attributed to movement.

Finally, results indicated that players' EF performance in general improved significantly from pre-to post task, which can be attributed to the experimental design itself. Since the players have performed the tasks twice in a relatively short period of time, learning effects must be considered independently of the group. However, performance differences related to the conditions and the detected trends in switch costs and flanker effect for response times cannot only be attributed to learning effects.

10. Implications and future directions

This study presents comprehensive assessments of EF under psychophysiological stress. The effectiveness of the implemented stressors was shown by means of physiological and psychological parameters. Investigation of the influence of stress on cognitive performance showed tendencies of performance improvements within the stress conditions but no significant effect across all players. In addition, as EF performance shows high interindividual differences (e.g., Beavan et al., 2020), we sought for intraindividual adaptations. Variability in cognitive performance was significantly reduced in incongruent and congruent trials of the soccer-specific flanker task after stress induction, indicating more stable cognitive performance.

Overall, our results support the assumption that EFs are shaped by situational factors such as stress that can subsequently cause alterations in performance (e.g., Henderson et al., 2012; Pnevmatikos & Trikkaliotis, 2013). Moreover, the results provide insights into situational psychophysiological adaptions to game-related stress and associated changes in cognitive processing. The additional assessment of potential influence factors on cognitive performance and the perception of a competitive situation could help to understand inter- and intra-individual differences. Accordingly, from a research perspective, we would advocate capturing relevant contextual information that reflects appraisal of the situation, including emotional and motivational states within cognitive diagnostics, and deliberately create game-like conditions in order to investigate different psychophysiological demands specifically. This could also help to gain further insight into whether EFs are developed domain-specific (e.g., Kalén et al., 2021) and are particularly pronounced through sports experience and expertise (Scharfen & Memmert, 2019) and how these factors moderate affective influences (Vaughan & McConville, 2021). Considering performance data is essential for the connection with actual game performance. In this context, data under soccer-specific demands, such as psychophysiological stress, might be more accurate than neutral data (Walton et al., 2018). Nevertheless, the data must also be considered in terms of position specificity as different positions require different behaviors. Thus, EFs may be more important for some players than others (Vestberg et al., 2020).

Moreover, this application of cognitive diagnostics also enables practical implications to derive individual training or interventions and thus the intraindividual changes due to stress are highly relevant from an applied perspective (Musculus et al., 2022). Coaches and sport psychologists could be able to identify players whose performance is affected by stress and help them to improve their appraisal and handling of stress or improve their cognitive performance under specific demands so that the effect of stress is less impairing. These insights could, therefore, provide an orientation to develop individual emotion regulation strategies and competition routines.

Based on our findings on reduced interference effects and performance variability related to stress, we would argue that this diagnostic form is more comprehensive for practitioners in the field and provides manifold individual insights for clubs compared to neutral testing. However, it is far more expensive and time-consuming for the clubs, so feasibility of the implementation is challenging.

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CRediT authorship contribution statement

S. Knöbel: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **A. Borchert:** Resources, Data curation, Resources, Data curation. **N. Gatzmaga:** Resources, Data Curation. **F. Heilmann:** Writing – review & editing. **L. Musculus:** Writing – review & editing, Methodology, Conceptualization. **S. Laborde:** Writing – review & editing, Resources, Methodology. **F. Lautenbach:** Writing – review & editing, Resources, Methodology, Conceptualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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